McKinsey
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The Bio Revolution

Innovations transforming economies, societies, and our lives

May 2020

McKinsey Global Institute

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Preface

Advances in biological sciences, combined with the accelerating development of computing, data processing, and artificial intelligence (AI), are fueling a new wave of innovation that could have significant impact in sectors across the economy, from healthcare and agriculture to consumer goods and energy.

This report describes the potential scope and scale of this wave of innovation and highlights the profound risks that will need to be managed. We conclude with a look at the potential implications for a range of stakeholders. The research began in early 2019, many months before the novel coronavirus SARS-CoV-2 causing the COVID-19 infection appeared and triggered a global pandemic in the first quarter of 2020. The early response to COVID-19 illustrated the substantial advances in biological science in just the past few years. The speed with which scientists sequenced the virus's genome—weeks rather than months—bore witness to the new world of biology we describe in this report. Sequencing is just the start: bio innovations are enabling the rapid introduction of clinical trials of vaccines, the search for effective therapies, and a deep investigation of both the origins and the transmission patterns of the virus. While this report does not explore the relevance of ongoing bio innovation to tackling COVID-19 in depth, we do believe that the pandemic makes this research even more acutely relevant.

The McKinsey Global Institute (MGI) has an active research program focused on research on technologies and their impact on business, the economy, and society, including in digital technology, AI, and biology. In May 2013, we published a report, *Disruptive technologies: Advances that will transform life, business, and the global economy*, that focused on biology as one of the arenas. Our 2017 report on automation, *A future that works: Automation, employment, and productivity,* highlighted the productivity potential of fast-evolving technologies but also looked at the technical and nontechnical factors that would determine the pace and extent of adoption. That same year, we published *Artificial intelligence: The next digital frontier?*, which examined how AI will unleash the next wave of digital disruption and what companies should do to prepare for it. McKinsey has also published reports on healthcare topics, including *The big-data revolution in US health care: Accelerating value and innovation* in 2013. In 2020, MGI plans to publish a major report on health and economic growth.

We owe a great deal to the wealth of academic and technical research into the many aspects of this wave of innovation. Building on MGI's expertise in analyzing the economic implications of major global trends, we surveyed the scientific advances and explored nearly 400 use cases, drawing out the implications for businesses, economies, and broader society. This research builds on previous MGI work on different types of disruptive technology, including big data, the Internet of Things, and, most recently, automation and AI. The project team worked closely with an MGI team researching global health issues in collaboration with McKinsey experts in public health and healthcare systems, and pharmaceuticals and medical products. We hope that this report contributes to a better understanding of the applications, potential, and risks of the advances in biological sciences and provokes further discussion among business leaders, policy makers, civil society, and the public on the potential benefits and trade-offs of these technologies given that they come with profound and unique risks.

The research was led by Michael Chui, MGI partner in San Francisco; Matthias Evers, a McKinsey senior partner based in Hamburg and McKinsey's global leader of R&D in pharmaceuticals and medical products; and James Manyika, McKinsey senior partner and co-chair of MGI. The work was also guided by Sven Smit, who also co-chairs MGI, and Jonathan Woetzel, MGI director in Shanghai. Alice Zheng and Travers Nisbet led the project team, which comprised Tom Colocci, Kevin Hwang, Maliha Khan, Archana Maganti, Morgan Paull, Anneke Maxi Pethö-Schramm, and Donna Xia. We thank Chloe Rivera and George Wang for leading the exploratory phase. We are grateful for the support of, and close collaboration with, Jaana Remes, Aditi Ramdorai, and Thilo Rattay on MGI research on global health issues. We also appreciated the opportunity to collaborate with Tim Dickson and Astrid Sandoval of *McKinsey Quarterly* and with Felix Rölkens, Shrina Poojara, and Marilena Schmich of McKinsey's *The state of fashion 2020* report.

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While we are grateful for all the input we have received, the report and views expressed here are ours alone. We welcome your comments on this research at MGI@mckinsey.com.

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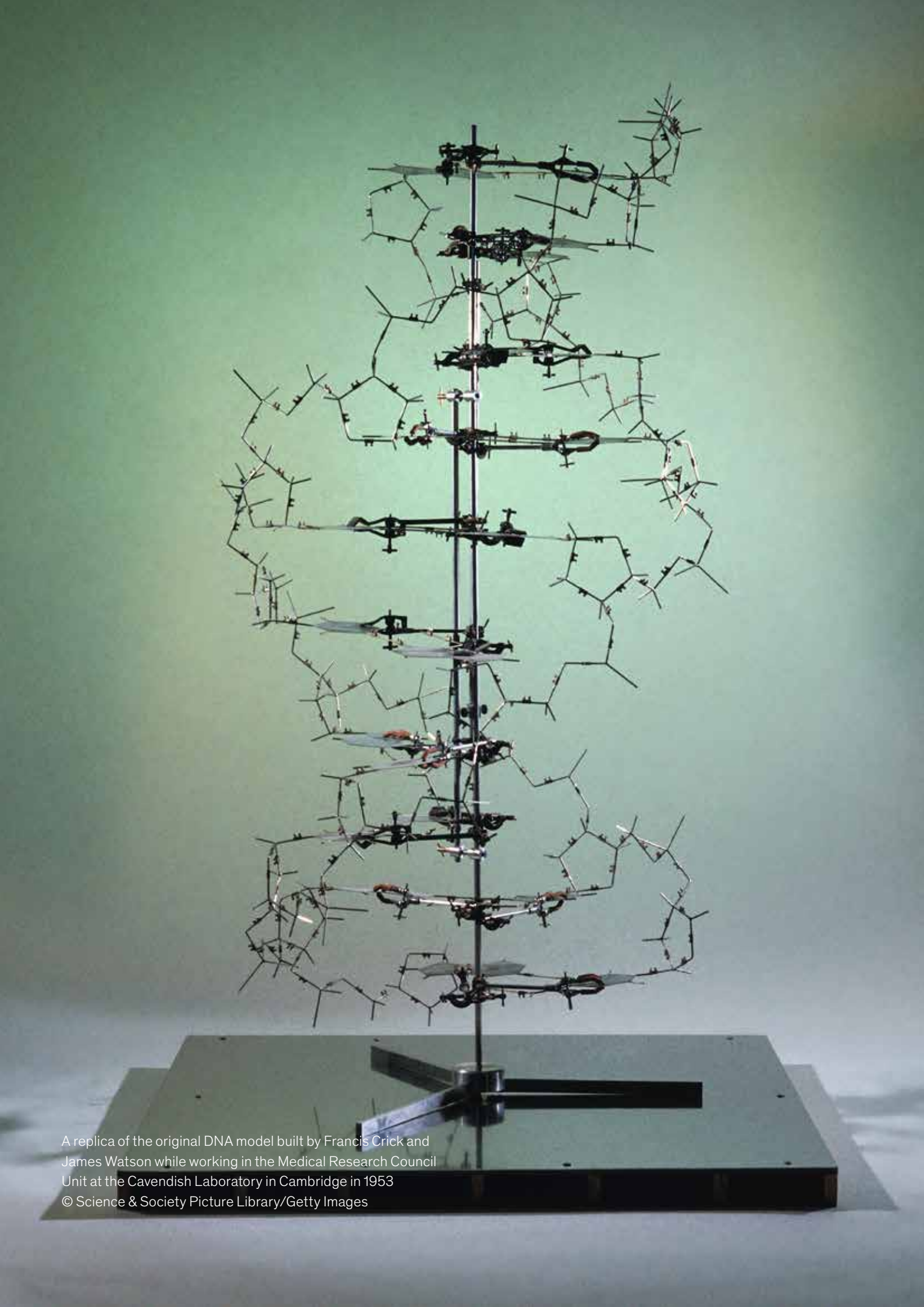

A replica of the original DNA model built by Francis Crick and James Watson while working in the Medical Research Council Unit at the Cavendish Laboratory in Cambridge in 1953
© Science & Society Picture Library/Getty Images

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In brief

The Bio Revolution

A confluence of advances in biological sciences—decades in the making—with the accelerating development of computing, automation, and artificial intelligence (AI), is fueling a new wave of innovation that could have significant impact on economies and societies, from health and agriculture to consumer goods and energy. These new capabilities and applications are already improving our response to global challenges from climate change to pandemics; at the time of writing this report, they were being used to help respond to the COVID-19 pandemic. But these innovations come with profound risks, arguing for a serious and sustained debate about how this innovative wave should proceed. This report assesses progress in these innovations, their potential for economic and societal impact, and the risks involved. Key findings include the following:

— **Increasing ability to understand and engineer biology.** Recent advances include a sharp drop in the cost of sequencing DNA and the emergence of new techniques (including CRISPR) to edit genes and reprogram cells. So far, innovation in four arenas stands out: (1) biomolecules—the mapping, measuring, and engineering of molecules; (2) biosystems—the engineering of cells, tissues, and organs; (3) biomachines—the interface between biology and machines; and (4) biocomputing—the use of cells or molecules such as DNA for computation. All show various rates of progress from demonstration to commercial use.

— **Transformative new capabilities.** These innovations are creating five new potentially transformative capabilities: (1) biological means could be used to produce a large share of the global economy's physical materials, potentially with improved performance and sustainability; (2) increased control and precision in methodology is occurring across the value chain from delivery to development and consumption with more personalization; (3) the capability to engineer and reprogram human and nonhuman organisms is increasing, potentially improving disease prevention and treatment as well as agricultural performance; (4) new methodologies using automation, machine learning, and proliferating biological data are enhancing discovery, throughput, and productivity in R&D; and (5) potential is growing for interfaces between biological systems and computers to, for instance, restore sensory function to the brain, and for biocomputers that could use DNA to store data.

— **Substantial potential direct and indirect impact.** As much as 60 percent of the physical inputs to the global economy could, in principle, be produced biologically—about one-third of these inputs are biological materials (wood or animals bred for food) and the remaining two-thirds are nonbiological (plastics or fuels) but could potentially be produced or substituted using biology. Therefore, it is possible that bio innovations could impact up to 60 percent of physical inputs, although attaining that full potential is a long way off. Even modest progress toward it could transform economies, societies, and our lives, including what we eat and wear, the medicines we take, the fuels we use, and how we construct our physical world. In human health, at least 45 percent of the current global disease burden could be addressed using science that is conceivable today.

— **Visible pipeline of applications.** Around 400 use cases, almost all scientifically feasible today, can be observed, mainly in human health and performance; agriculture, aquaculture, and food; consumer products and services; and materials, chemicals, and energy production. These use cases alone—more than half of which fall outside human health—could have direct economic impact of up to $4 trillion a year over the next ten to 20 years. The full potential could be far larger if we take into account potential knock-on effects, new applications yet to emerge, and additional scientific breakthroughs.

— **Unique risks that require debate and mitigation.** New biological capabilities come with profound and unique risks that need serious, ongoing debate, and proactive, rather than reactive, approaches toward mitigation. One such risk is that biological systems are self-sustaining, self-replicating, and interconnected, with potentially cascading and long-lasting effects on entire ecosystems or species; once Pandora's box is opened, we could have little control over what happens next. Access to these tools may be relatively cheap and easy, making the potential for misuse considerable. Privacy and consent issues abound due to new forms of biological data. Responding to such challenges through cooperation and coordination may be complicated given competitive and commercial incentives and varying jurisdictional or cultural value systems.

— **The timing of applications' adoption and impact hinges on multiple factors.** Adoption timelines, and therefore impact, will vary depending on several factors, including society's approach to risks. There are three stages in the journey from lab to market: scientific research, commercial availability, and diffusion at scale. Science needs investment and to be proven. Resulting applications need to offer a value proposition against existing offerings, and able to be scaled. Diffusion and eventual impact will depend on public sentiment and mechanisms governing the use of different applications. About 70 percent of the total potential impact could hinge on societal attitudes and the respective mechanisms employed to govern use, such as regulations and societal norms.

— **Stakeholders and contributors need to inform themselves about the Bio Revolution.** Innovators, businesses, governments, and citizens need to become bio-literate in order to respond effectively to ongoing bio innovation, weighing risk against reward. The choices they make will influence the size and scope of the Bio Revolution's benefits for economies, societies, and the planet.

The Bio Revolution

Four arenas of bio innovations

Biomolecules
Mapping and engineering intracellular molecules

Biosystems
Mapping and engineering cells, tissues, and organs

Biomachine interfaces
Connecting nervous systems of living organisms to machines

Biocomputing
Using cells and cellular components for computation

The scope and scale of the potential impact on economies and societies appear substantial

60% of the world's physical inputs could be made using biological means

45% of the world's disease burden could be addressed

30% of private-sector R&D spent in biology-related industries

Transformative new capabilities...

- **Bio-based materials production**
- **Personalized and precision products and services**
- **Engineered organisms**
- **Higher bio-based R&D productivity**
- **Bio-machine interfaces and computing**

...with applications across domains

Examples of applications

Agriculture
Meats produced without animals

Energy and materials
Synthetic silks produced by microbe factories

Health
Monogenic diseases prevented at birth

Consumers
Personalized diets based on your genome

...but risks and issues to manage

- Self-replicating, bio crossing borders
- Unintended consequences
- Low barriers to potential misuse
- Hard to forge consensus
- Privacy and consent concerns
- Inequitable access or effects

$2T–$4T

of annual direct economic potential globally in 2030–40
(significantly higher with downstream and secondary effects)

Innovators, businesses, and policy makers must act if we are to capture the benefits of the Bio Revolution, while engaging together in a sustained dialogue about how to use these innovations

McKinsey Global Institute

Executive summary

Nearly seven decades after the double helix structure of a DNA molecule was discovered, the world of biology appears to have reached a new phase of growth. A flurry of recent innovations—such as CRISPR–Cas9 to edit genes and stem cell advances to reprogram cells—are providing new understanding, new materials, and new tools, as well as lower costs. The science is so advanced, for example, that in 2016, a Human Cell Atlas project was kicked off to create comprehensive reference maps of all human cells as a basis for research, diagnosis, monitoring, and treatment. Moreover, as a result of the scientific advances, a growing number of applications are emerging from the lab and being put to commercial use.[1]

The potential for beneficial economic and social impact seems enormous. As much as 60 percent of the physical inputs to the global economy could, in principle, be produced biologically. Our analysis suggests that around one-third of these inputs are biological materials, such as wood, cotton, and animals bred for food. For these materials, innovations can improve upon existing production processes. For instance, squalene, a moisturizer used in skin-care products, is traditionally derived from shark liver oil and can now be produced more sustainably through fermentation of genetically engineered yeast. The remaining two-thirds are not biological materials—examples include plastics and aviation fuels—but could, in principle, be produced using innovative biological processes or be replaced with substitutes using bio innovations. For example, nylon is already being made using genetically engineered microorganisms instead of petrochemicals. To be clear, reaching the full potential to produce these inputs biologically is a long way off, but even modest progress toward it could transform supply and demand and economics of, and participants in, the provision of physical inputs. Biology has the potential in the future to determine what we eat, what we wear, the products we put on our skin, and the way we build our physical world.

Human health is one of the most significant domains where biological advances are being applied. Biology is already helping save lives through innovative treatments tailored to our genomes and microbiomes. In the future, we estimate that almost half of the global disease burden could be addressed through applications that are scientifically conceivable today. Moreover, many of the innovations born of these bio innovations contributed to the global response to the SARS-CoV-2 pandemic in early 2020 (see Box E1, “An April 2020 snapshot of early contributions by bio innovations in the fight against COVID-19,” at the end of this executive summary).

[1] DNA is short for deoxyribonucleic acid, an organic chemical found in all cells and in many viruses. DNA acts as the main carrier for genetic information. CRISPR-Cas9 stands for clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9. This tool uses a small piece of ribonucleic acid (RNA) with a short “guide” sequence that attaches to a target sequence of DNA and to the Cas9 enzyme. The Cas9 enzyme cuts the targeted DNA at the targeted location, which enables genetic material to be added or deleted. In the rest of this report, we refer to the tool as CRISPR. RNA is a biopolymer consisting of ribose nucleotides (nitrogenous bases appended to a ribose sugar molecule) connected and forming strands of varying lengths. Unlike most DNA molecules composed of two biopolymer strands, RNA typically is a single-stranded biopolymer. RNA molecules play essential biological roles, from translating genetic information encoded in DNA molecules into the cellular structures and molecular machines (that is, proteins) to regulating the activities of genes. A stem cell is a type of cell in a multicellular organism that has two capabilities: self-renewal by producing indefinitely more cells of the same type, and the ability to give rise to many other kinds of cells in the body by differentiation.

Many other domains, from agriculture to energy, could also benefit from biological processes and products. Biology could even be deployed to mitigate climate change, by helping reduce net man-made greenhouse gas (GHG) emissions.

However, the risks from these innovations are profound and unique. Biological systems self-replicate, are self-sustaining, and are highly interconnected; changes to one part of a system can have cascading effects and unintended consequences across an entire ecosystem or species. Accidents can have major consequences—and, especially if used unethically or maliciously, manipulating biology could become a Pandora's box that, once opened, unleashes lasting damage to the health of humans, ecosystems, or both. The risks are particularly acute because many of the materials and tools are relatively cheap and accessible. Moreover, tackling these risks is complicated by a multiplicity of jurisdictional and cultural value systems, which makes collaboration and coordination across countries difficult.

This report, which draws on a wealth of academic and technical research, takes a detailed look at how advances in biological science and their practical application could transform our economy and society. We have compiled a library of about 400 visible use cases that, while not comprehensive, nonetheless point to the domains that could be most directly affected—and hint at the potential economic value that could be created. We also focus on the considerable challenges that will need to be overcome to turn biology's economic potential into reality in scientific research, commercialization, and diffusion. By our estimate, more than two-thirds of the total impact could hinge on consumer, societal, and regulatory acceptance of these applications. A new era is dawning that we refer to as the Bio Revolution. Like all periods of economic and technological disruption, it is an era of both great opportunity and considerable uncertainty.

Bio innovation is occurring in four key arenas

A wave of innovation is being enabled by advances in biological sciences accelerated by developments in computing, data analytics, machine learning, AI, and biological engineering. We group innovations into four arenas: biomolecules, biosystems, biomachine interfaces, and biocomputing (Exhibit E1).[2]

[2] Our definition of biomolecules for this report covers the mapping and measuring of intra-cellular components (for example, DNA, RNA, and proteins) in the study of omics. We also include the engineering of intra-cellular components (for instance, genome editing). Our definition of biosystems covers engineering at the cell, tissue, or organ level, including stem-cell technologies and transplantation use cases. Biomachine interfaces is a field of biology defined as the connection of nervous systems of living organisms to machines, including in brain-machine interfaces. Biocomputing is a field of biology defined as using cells and cellular components for computational processes (storing, retrieving, or processing data).

Exhibit E1

Bio innovation is occurring in four key arenas.

	Biomolecules	Biosystems	Biomachine interfaces	Biocomputing
Definitions				
Mapping	Cellular processes and functions via measuring intracellular molecules (eg, DNA, RNA, proteins) in the study of omics	Complex biological organizations and processes, and interactions between cells	The structure and function of nervous systems of living organisms	Intracellular pathways or networks of cells to return outputs based on specific conditions (for computation)
Engineering[1]	Intracellular molecules (eg, via genome editing)	Cells, tissues, and organs, including stem cell technologies and transplantation	Hybrid systems that connect nervous systems of living organisms to machines	Cells and cellular components for computational processes (storing, retrieving, processing data)
Examples	Gene therapy for monogenic diseases	Cultured meat grown in a lab	Neuroprosthetics for motor control (implant or external headset) of human or robotic limb	Data storage in strands of DNA

1. Design, de novo synthesis, or modification.
Source: McKinsey Global Institute analysis

Major breakthroughs in each of the four arenas are reinforcing one another. In biomolecules and biosystems, advances in omics and molecular technologies—the mapping and measuring of molecules and pathways within cells, and engineering them—are enhancing our understanding of biological processes, as well as enabling us to engineer biology (Exhibit E2).[3] For example, CRISPR technology allows scientists to edit genes more quickly and precisely than previous techniques. Advances in biomachines and biocomputing both involve deep interaction between biology and machines; it is becoming increasingly possible to measure neural signals and power precise neuroprosthetics.[4] It is now also possible to store the world's wealth of data using DNA—by some measures one kilogram of DNA could hypothetically store all current data in the world.[5]

3 Omics is a collective term for technologies that allow the comprehensive identification and quantification of the complete set of molecules (for instance, proteins, carbohydrates, and lipids) of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time. Omics and molecular technologies is defined to cover the study of omics as well as technologies to engineer (design, synthesize, or modify) the same "omes."

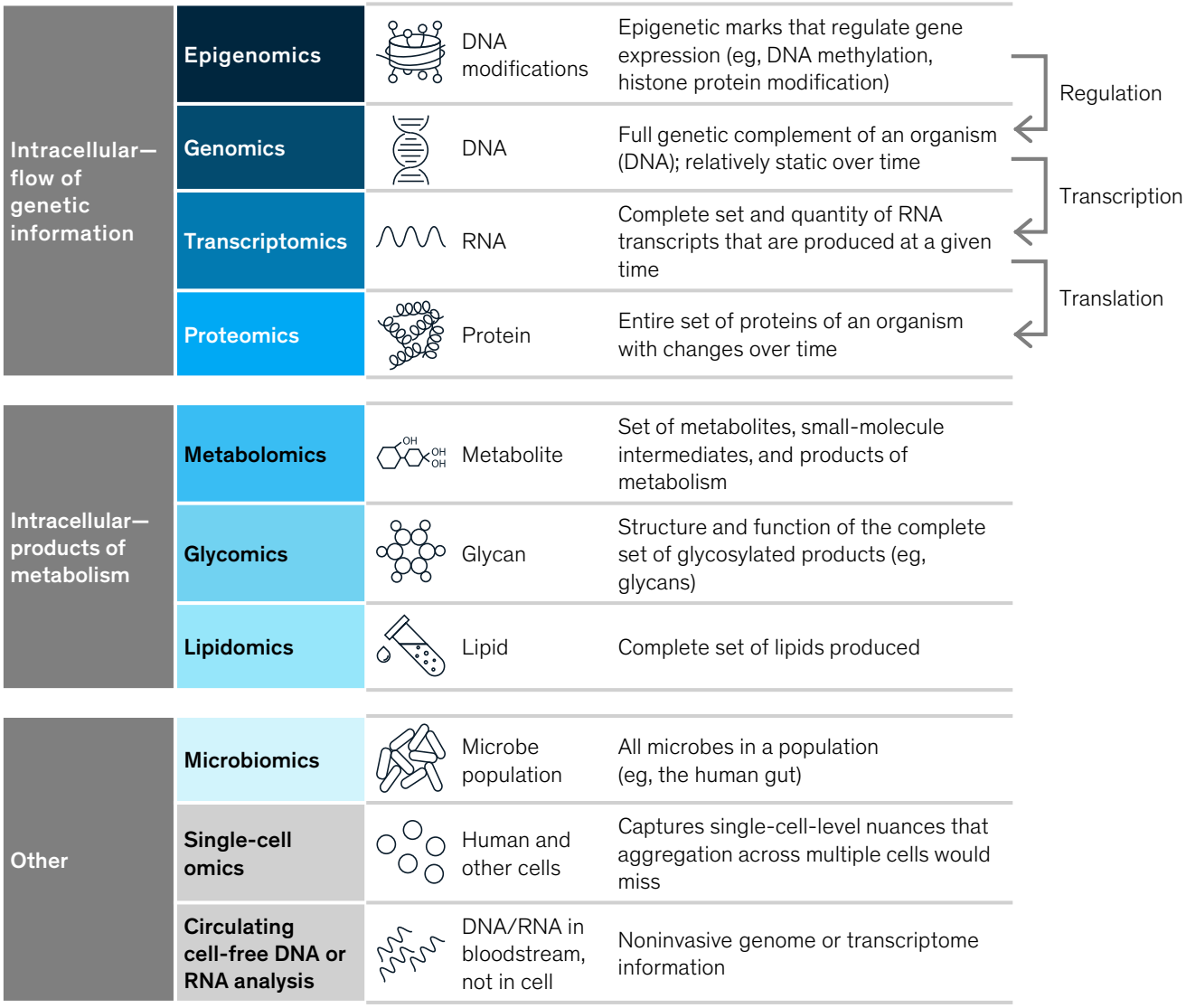
4 Neuroprosthetics are hybrid bionic systems that link the human nervous system to computers, thereby providing motor control and restoring lost sensory function of artificial limbs.

5 Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016; and George I. Seffers, "Scientists race toward DNA-based data storage," *Signal*, September 1, 2019.

Worldwide DNA sequencing now creates huge volumes of biological data every year.[6] These technical advances, such as lower-cost sequencing or high-throughput screening, have helped lower the costs of entry, accelerate the pace of experimentation, and generate new forms of data to help us better understand biology. Advances at the single-cell level, such as single-cell imaging tools and single-cell ribonucleic acid (RNA) sequencing, are allowing scientists to build increasingly high-resolution maps of cells, which can be a basis for research, diagnosis, and treatment. Increasingly, the ability to understand and engineer biological processes exists across a variety of dimensions.

Exhibit E2

A range of scientific research streams are collectively known as omics.


Intracellular—flow of genetic information
Epigenomics
DNA modifications
Epigenetic marks that regulate gene expression (eg, DNA methylation, histone protein modification)
Genomics
DNA
Full genetic complement of an organism (DNA); relatively static over time
Transcriptomics
RNA
Complete set and quantity of RNA transcripts that are produced at a given time
Proteomics
Protein
Entire set of proteins of an organism with changes over time
Regulation
Transcription
Translation
Intracellular—products of metabolism
Metabolomics
Metabolite
Set of metabolites, small-molecule intermediates, and products of metabolism
Glycomics
Glycan
Structure and function of the complete set of glycosylated products (eg, glycans)
Lipidomics
Lipid
Complete set of lipids produced
Other
Microbiomics
Microbe population
All microbes in a population (eg, the human gut)
Single-cell omics
Human and other cells
Captures single-cell-level nuances that aggregation across multiple cells would miss
Circulating cell-free DNA or RNA analysis
DNA/RNA in bloodstream, not in cell
Noninvasive genome or transcriptome information

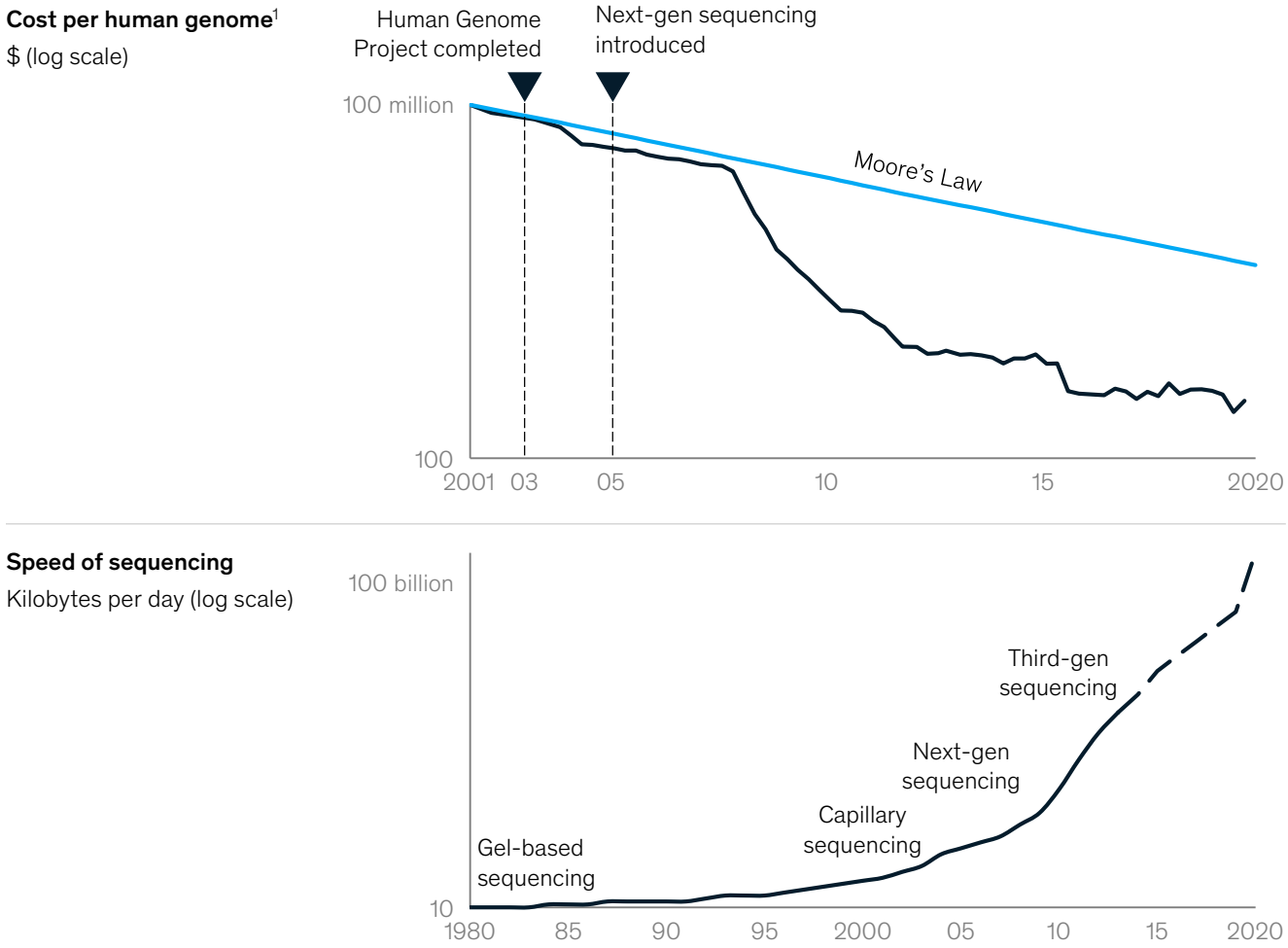
Source: McKinsey Global Institute analysis

[6] Erika Check Hayden, "Genome researchers raise alarm over big data," *Nature*, July 1, 2015.

Mapping the genome is a foundational building block. This dates to the Human Genome Project, a 13-year, $3 billion journey to map the entire genetic makeup of humans, that began in 1990.[7] Accordingly, genomics is the most technologically advanced branch of omics, and has the most related applications either in development or already in use.[8] But other omics are necessary complements, and work on them is increasing. However, the power of the map of the human genome began to materialize only when sequencing DNA became cheaper and faster. The cost of DNA sequencing is now decreasing at a rate faster than Moore's Law (Exhibit E3).[9] In 2003, mapping the human genome cost about $3 billion; by 2019, it was less than $1,000. Within a decade or even sooner, the cost could be less than $100.[10]

Exhibit E3

Rapid advances in computing, bioinformatics, and AI are enabling the analysis of omics data.



1. Data do not capture all costs associated with genome sequencing and include only production-related costs (labor, instruments, informatics, data submission).

Source: National Human Genome Research Institute; www.yourgenome.org; McKinsey Global Institute analysis

7 Human Genome Project Information Archive 1990–2003, https://web.ornl.gov/sci/techresources/Human_Genome/index.shtml.

8 Genomics is the study of genes and their functions, and techniques related to them. The genome consists of the full genetic complement of an organism—its DNA.

9 Moore's Law refers to the perception that the number of transistors on a microchip doubles every two years even while the cost of computers halves. See Gordon Moore, "Cramming more components onto integrated circuits," originally in *Electronics*, April 19, 1965, Volume 38, Number 8.

10 Kristen V. Brown, "A $100 genome is within reach, Illumina CEO asks if world is ready," Bloomberg, February 27, 2019; Antonio Regalado, "China's BGI says it can sequence a genome for just $100," *MIT Technology Review*, February 26, 2020.

New biological capabilities could bring about transformational change in economies, societies, and our lives

New biological capabilities have the potential to bring sweeping change to economies and societies. The effects will be felt across value chains, from how R&D is conducted to the physical inputs in manufacturing to the way medicines and consumer products are delivered and consumed. These capabilities include the following:

— **Biological means could be used to produce a large share of the global economy's physical materials, potentially with improved performance and sustainability.** Significant potential exists to improve the characteristics of materials, reduce the emissions profile of manufacturing and processing, and shorten value chains. Fermentation, for centuries used to make bread and brew beer, is now being used to create fabrics such as artificial spider silk. Biology is increasingly being used to create novel materials that can raise quality, introduce entirely new capabilities, be biodegradable, and be produced in a way that generates significantly less carbon emissions. Mushroom roots rather than animal hide can be used to make leather.[11] Plastics can be made with yeast instead of petrochemicals.

— **Increased control and precision in methodology is occurring across the value chain, from delivery to development and consumption with more personalization.** Advances in biological sciences have made R&D and delivery processes more precise and predictable; the character of R&D is shifting from discovery by accident to rational design. Increasing knowledge of human genomes and the links between certain genes and diseases is enabling the spread of personalized or precision medicine, which can be more effective than the one-size-fits-all therapies of the past.[12] Precision also applies to agriculture, where insights from a plant or soil's microbiome increasingly can be used to optimize yield as well as to offer consumers with, for instance, personalized nutrition plans based on genetic tests.[13]

— **The capability to engineer and reprogram human and nonhuman organisms is increasing.** Gene therapies could offer complete cures of some diseases for the first time. The same technical advances that are driving capabilities that improve human health can be used to introduce valuable new traits that, for instance, improve the output or yield of nonhuman organisms like microbes, plants, and animals. Crops can be genetically engineered to produce higher yields and be more heat- or drought-resistant, for instance. By permanently genetically altering the vectors spreading disease (such as mosquitoes), gene drives could be used to prevent vector-borne diseases, including malaria, dengue fever, schistosomiasis, and Lyme disease, although they also come with ecological risks.[14]

— **New methodologies using automation, machine learning, and proliferating biological data are enhancing discovery, throughput, and productivity in R&D.** Biology and computing together are accelerating R&D, thereby addressing a productivity challenge. McKinsey analysis in 2017 found that the ratio of revenue to R&D spending in the biopharmaceutical industry hit a low point in productivity between 2008 and 2011.[15] An explosion of biological data due to cheaper sequencing can be used by biotech companies and research institutes that increasingly are using robotic automation and

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11 Thomas Crow, "Mushroom leather: The key to sustainable fashion?," *Particle*, April 2019; and Eillie Anzilotti, "This very realistic fake leather is made from mushrooms, not cows," Fast Company, April 2018.

12 For a fuller description, see, for example, *The Precision Medicine Initiative*, obamawhitehouse.archives.gov/precision-medicine.

13 Chrysi Sergaki et al., "Challenges and approaches in microbiome research: From fundamental to applied," *Frontiers in Plant Science*, August 2018, Volume 9; Aleksandra A. Kolodziejczyk, Danping Zheng, and Eran Elinav, "Diet-microbiota interactions and personalized nutrition," *Nature Reviews Microbiology*, December 2019, Volume 17, Issue 12; Monica Reinagel, "Personalized nutrition: The latest on DNA-based diets," *Scientific American*, September 27, 2019; and Anna Vesnina et al., "Genes and eating preferences, their roles in personalized nutrition," *Genes*, April 2020, Volume 11, Issue 4.

14 A gene drive is a technology that uses genetic engineering to enable a specific genetic variant to be passed from parent to child at a higher-than-normal rate (up to 100 percent).

15 Sastry Chilukuri, Edd Fleming, and Ann Westra, *Digital in R&D: The $100 billion opportunity*, McKinsey & Company, December 2017.

sensors in labs that could increase throughput up to ten times.[16] Further, advanced analytics, more powerful computational techniques, and AI can be leveraged to provide better insights during the R&D process.

— **Potential is growing for interfaces between biological systems and computers.** A new generation of biomachine interfaces relies on close interaction between humans and computers. Such interfaces include neuroprosthetics that restore lost sensory functions (bionic vision) or enable signals from the brain to control physical movement of prosthetic or paralyzed limbs. Biocomputers that employ biology to mimic silicon, including the use of DNA to store data, are being researched. DNA is about one million times denser than hard-disk storage; technically, one kilogram of DNA could store the entirety of the world's data (as of 2016).[17]

While these are early days, the scope and scale of these emerging capabilities could have a broad impact on economies and societies, touching multiple domains both directly and indirectly. These applications may change everything from the food we consume to textiles to the types of health treatments we receive and how we build our physical world. The potential value is vast. As noted, as much as 60 percent of the physical inputs to the global economy could be produced biologically, and even modest progress toward that 60 percent number could be transformative.

Beyond the physical world, innovations could transform prevention, diagnostics, and treatment of disease. At least 45 percent of the global disease burden could be addressed with capabilities that are scientifically conceivable today, according to our analysis.

Bio innovations, such as high-throughput screening, CRISPR, and machine learning for analyzing large and complex biological data, have also begun to shape R&D. We estimate that roughly 30 percent of private-sector R&D in major economies is in industries where biological data, biological inputs, or biological means of production could be used.[18]

The full impact remains some way off in the future. But already, it is possible to identify some key applications and domains where these technologies could be deployed. Over the past five to ten years, proof-of-concept experimentation has increasingly emerged from the lab and moved into the marketplace. Many applications, particularly in health and agriculture, are now in the commercialization phase. Products from materials to chemicals are being substituted by alternatives produced and processed using biological means that are often more efficient and, in many cases, put less pressure on the environment. While the early direct impacts of biological technologies are for now primarily concentrated in certain domains, such as human health and agriculture, they could spread downstream to other sectors and society more broadly.

A visible pipeline of applications can deliver profound impact across a wide range of domains in the next two decades

To examine a wide range of applications, we compiled a library of about 400 use cases. They constitute an already-visible pipeline for the years ahead. Our library included use cases that are scientifically conceivable today and that could plausibly be commercialized by 2050. We excluded use cases that are not scientifically conceivable today or that are unlikely to have material commercial impact by 2050. The library is extensive, but not exhaustive—for instance, our research utilized publicly available data, but there are many applications being developed in private labs or in the defense industry where confidentiality reigns. We estimated the direct impact by sizing four value gain drivers: reduced disease burden;

[16] *Zymergen case studies*, Partnership on AI, partnershiponai.org/case-study/zymergen/; Melanie de Almeida, *Taking biotech to the next level with laboratory automation*, Labiotech, November 14, 2018.
[17] Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016.
[18] R&D funded by business enterprise sector across major regions such as China, the EU, and the United States. Analysis is based on data from EU Industrial R&D Investment Scoreboard (2019).

improved quality; cost productivity; and environmental benefit. These estimates of potential value did not include knock-on effects. Using expert input and historical analogs, we then extrapolated our assessed impact to different time horizons by estimating the level and pace of adoption, as discussed below.[19]

Over the next ten to 20 years, we estimate that these applications alone could have direct economic impact of between $2 trillion and $4 trillion globally per year (Exhibit E4). Whether the impact is toward the bottom or top of that range will depend on how and when innovations are adopted. As we discuss below, significant uncertainty surrounds both scientific feasibility and commercial availability. The potential could be significantly higher if downstream and secondary effects are taken into account, as discussed in the next section.

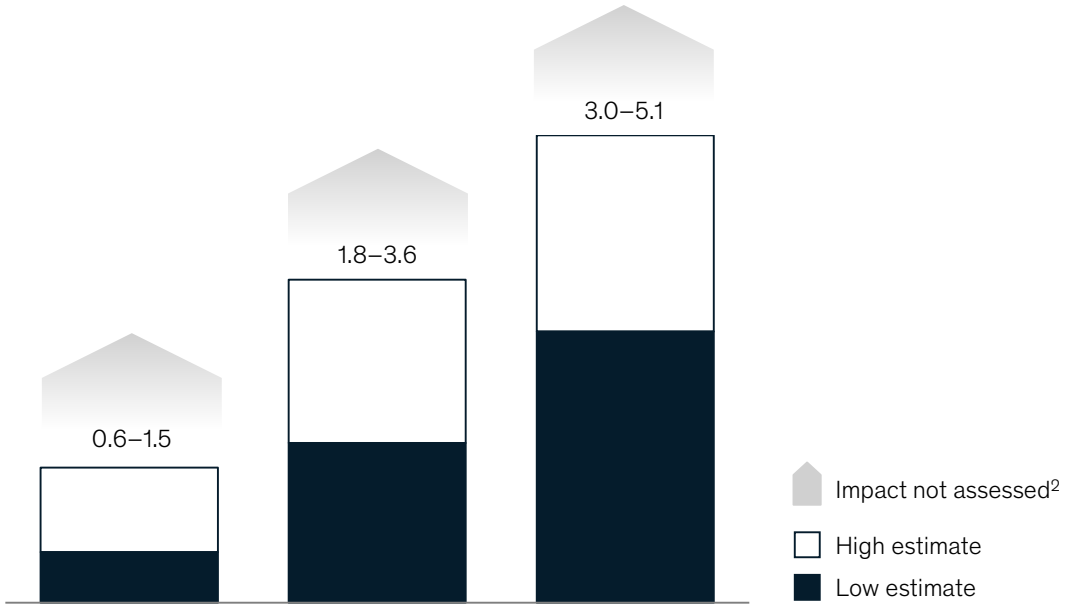
Human health and performance have the most scientific advances and the clearest pipeline from research to application. The science is advanced, and the market is generally accepting of innovations. However, based on our use cases, the impact could be more broad-based; in the next ten to 20 years, more than half of the direct impact is likely to be outside health, primarily in agriculture and consumer products (Exhibit E5).

Exhibit E4

In ten to 20 years, a visible pipeline of biological applications could create approximately $2 trillion to $4 trillion of direct annual economic impact.

Partial estimate of potential and direct annual impact by time horizon[1]

$ trillion



1. Current figures are based on potential direct annual economic impacts from 400 use cases examined, excluding non-omic economic impact from biocomputing and half of the biomachine applications.
2. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.

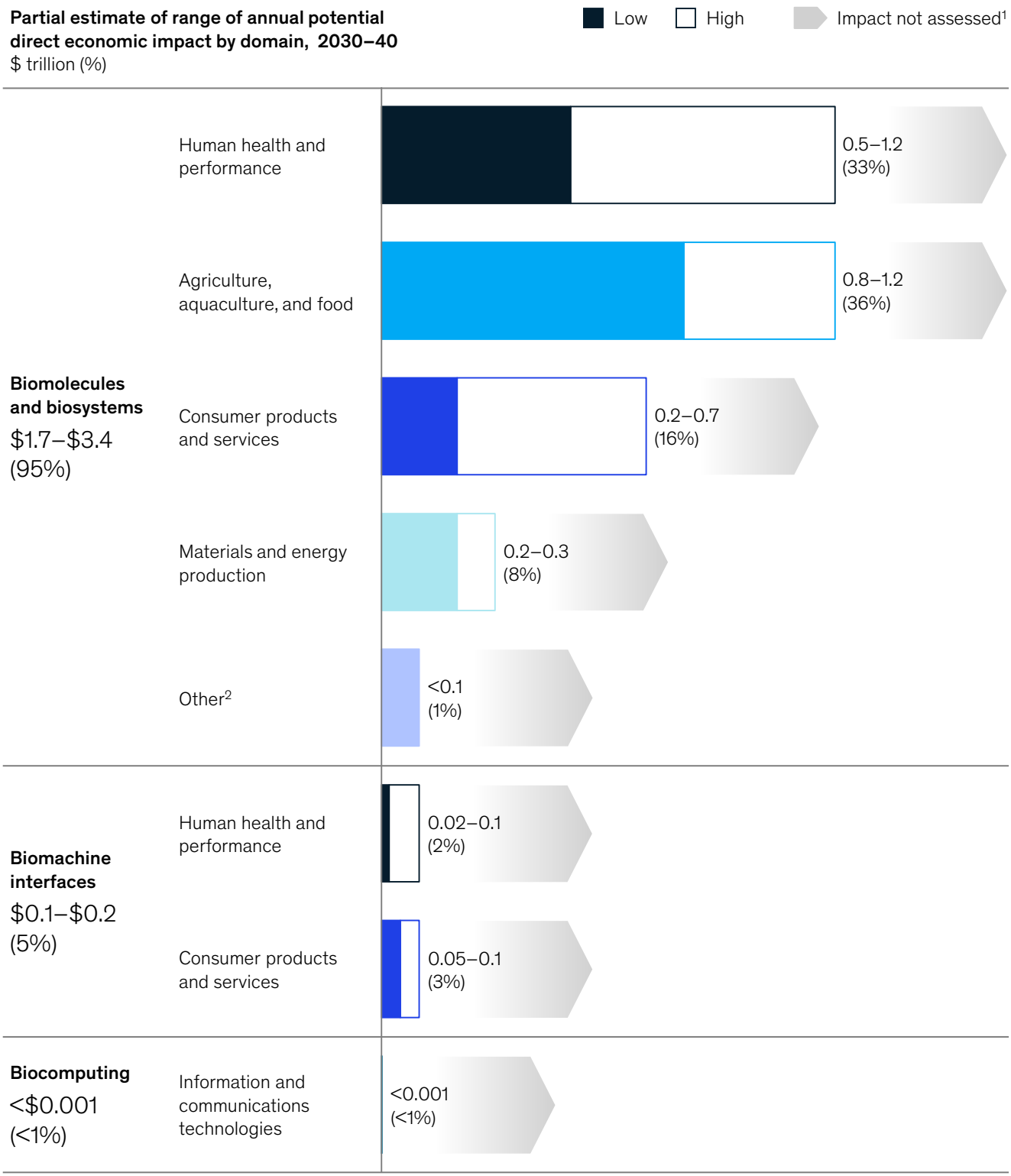
Source: McKinsey Global Institute analysis

[19] For more on the methodology, please see chapter 4 and the technical appendix.

Exhibit E5

More than half of the impact from the visible pipeline of applications is outside of healthcare—in agriculture, consumer, and other areas.

Partial estimate of range of annual potential direct economic impact by domain, 2030–40
$ trillion (%)



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
2. Other applications include defense and security, undoing environmental harm, and education and talent.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation. Percentage of total impact is based on the midpoint of our estimated range of annual potential direct economic impact.

Source: McKinsey Global Institute analysis

Our library of use cases suggests that most value in the next one to two decades will come in four domains, or clusters of sectors where applications are emerging from bio innovation. Here we summarize use cases in each of these key domains (for a detailed snapshot, see illustration, "Applying the Bio Revolution for broad impact").[20]

— **Human health and performance.** A new wave of innovation is under way that includes cell, gene, RNA, and microbiome therapies to treat or prevent disease, innovations in reproductive medicine such as carrier screening, and improvements to drug development and delivery.[21] Many more options are being explored and becoming available to treat monogenic (caused by mutations in a single gene) diseases such as sickle cell anemia, polygenic diseases (caused by multiple genes) such as cardiovascular disease, and infectious diseases such as malaria.[22] We estimate between 1 and 3 percent of the total global burden of disease could be reduced in the next ten to 20 years from these applications—roughly the equivalent of eliminating the global disease burden of lung cancer, breast cancer, and prostate cancer combined. Over time, if the full potential is captured, 45 percent of the global disease burden could be addressed using science that is conceivable today. The direct annual global potential impact in this domain is estimated at $500 billion to $1.3 trillion over the next ten to 20 years, or 35 percent of the overall impact that we estimate for this period. The main capabilities enabling impact are the increased precision and personalization in the delivery of treatment and the accelerated pace and scope of R&D. In the longer term, innovations are likely to spread to more therapeutic areas such as cardiovascular and neurodegenerative diseases.

— **Agriculture, aquaculture, and food.** Applications such as low-cost, high-throughput microarrays have vastly increased the amount of plant and animal sequencing data, enabling lower-cost artificial selection of desirable traits based on genetic markers in both plants and animals.[23] This is known as marker-assisted breeding and is many times quicker than traditional selective breeding methods.[24] In addition, in the 1990s, genetic engineering emerged commercially to improve the traits of plants (such as yields and input productivity) beyond traditional breeding.[25] Historically, the first wave of genetically engineered crops has been referred to as genetically modified organisms (GMOs); these are organisms with foreign (transgenic) genetic material introduced.[26] Now, recent advances in genetic engineering (such as the emergence of CRISPR) have enabled highly specific cisgenic changes (using genes from sexually compatible plants) and intragenic changes (altering gene combinations and regulatory sequencings belonging to the recipient plant).[27] Other innovations in this domain include using the microbiome of plants, soil, animals, and water to improve the quality and productivity of agricultural production; and the development of alternative proteins, including lab-grown meat, which could take pressure off the environment from traditional livestock and seafood. Direct annual impact from all applications in this domain could be between about $800 billion and $1.2 trillion over the next ten to 20 years, or 36 percent of the total.

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20 For an in-depth discussion of applications across domains studied in this research, see chapter 6.

21 Carrier screening is a genetic test used to determine if a healthy person is a carrier of a recessive genetic disease. It provides life-lasting information about an individual's reproductive risk and their chances of having a child with a genetic disease.

22 Polygenic diseases are caused by more than one gene. Examples of polygenic conditions include hypertension, diabetes, and coronary heart disease. There are often many environmental factors, too, making it more difficult to discern to what degree a disease is genetic even when the multiple genes are identified.

23 A microarray is a high-throughput screening method where the DNA sequences representing the large number of genes of an organism, arranged in a grid pattern for detection in genetic testing.

24 Marker-assisted breeding uses DNA markers associated with desirable traits to enable breeders to select a trait of interest without using transgenic approaches. Therefore, marker-assisted breeding doesn't produce genetically engineered organisms.

25 National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*, Washington, DC: The National Academies Press, 2016.

26 A GMO is an organism whose genetic material has been altered or modified. In GM crops, DNA from foreign organisms such as bacteria are introduced. See Kaare M. Nielsen, "Transgenic organisms—time for conceptual diversification?," *Nature Biotechnology*, March 2003, Volume 21, Issue 3.

27 National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*, Washington, DC: The National Academies Press, 2016.

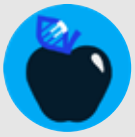
— **Consumer products and services.** Opportunities are opening up to use increasing volumes of biological data to offer consumers personalized products and services based on their biological makeup. Applications include direct-to-consumer (DTC) genetic testing, beauty and personal care based on microbiomes, and innovative approaches to wellness and fitness in both humans and pets. Some of these applications could have indirect impact on human health, such as wellness or fitness applications.[28] Annual direct economic impact over the next ten to 20 years in this domain could be $200 billion to $800 billion, or 19 percent of the total. Roughly two-thirds of this may come from the capability to personalize.

— **Materials, chemicals, and energy.** New biological ways of making and processing materials, chemicals, and energy could transform many industries and our daily lives, although the economics are challenging. Improved fermentation processes can increase the speed of production or quality of materials that are already created using fermentation (such as food and feed ingredients). Further, the creation of new bioroutes can enable the manufacture of more materials and chemicals biologically and the production of completely novel materials. Finally, advances are being made in energy, with greater use of biofuels, improving energy extraction, and improving energy storage. Applications include innovations related to production of materials such as improved fermentation processes, new bioroutes utilizing the ability to edit the DNA of microbes to develop novel materials with entirely new properties (self-repairing fabrics are one example), and building on advances in biofuels to innovate new forms of energy storage. Over the next ten to 20 years, the direct annual global impact could be $200 billion to $300 billion a year, or 8 percent of the total. This is a conservative estimate given uncertainty about what novel materials may emerge and the historical challenges of scaling innovations in this domain. About three-quarters of this economic potential is related to improved resource efficiency from new methods of production.

Biology has many other potential applications, although some of these are likely to be further in the future. It could be deployed to help the environment through biosequestration—using biological processes to capture carbon emissions from the atmosphere—and bioremediation, which is a process to remove inorganic and organic compounds from soil, water, and the atmosphere that might be harmful. Other potential applications could be found in education, defense, and even space exploration. While we expect biomolecules and biosystems innovations will drive the largest direct impact across the range of domains, impact is also emerging in biomachine interfaces and biocomputing, where the science and development are at an early stage but applications are promising. Applications that have already been developed include neuroprosthetics to restore hearing and vision.

[28] We include wellness, nutrition, and fitness in consumer products and services rather than health because they tend to be consumed directly by individuals rather than mediated by healthcare professionals, offer more consumer choice compared to traditional health applications, and in some cases, such as fitness, require a significant change in consumer behavior to realize positive impact. This domain also includes beauty/enhancement use cases.

Applying the Bio Revolution …

Domain and examples	Arenas of innovation	Transformational capabilities
Human health and performance Health optimization in future generations Gene drives to reduce vector-borne diseases Cell-, gene-, and RNA-based approaches to prevent, diagnose, and treat diseases Improvements in drug development and delivery	Biomolecules Biosystems Biomachine interfaces	Increased control and precision Enhanced ability to engineer and reprogram human and non-human organisms Increased throughput and productivity of R&D Growing potential for interfaces between biological systems and computers
Agriculture, aquaculture, and food Selective breeding of animals and plants  CRISPR genetic engineering of plants Growth of plant-based protein and lab-grown meat Microbiome data to optimize agricultural inputs	Biomolecules Biosystems	Biological means for physical inputs Increased control and precision Enhanced ability to engineer and reprogram human and non-human organisms Increasing throughput and productivity of R&D
Consumer products and services DTC genetic testing Microbiome-based beauty products Genetically engineered pets Personalized offering of health, nutrition, and fitness based on omics data	Biomolecules Biosystems Biomachine interfaces	Increased control and precision Growing potential for interfaces between biological systems and computers
Materials, chemicals, and energy Development of new bioroutes for fabrics and dyes Improvement of existing fermentation processes for industrial enzymes Development of novel materials such as biopolymers Extraction of raw materials using microbes	Biomolecules Biosystems	Biological means for physical inputs Enhanced ability to engineer and reprogram human and non-human organisms Increasing throughput and productivity of R&D

… for broad impact

Annual potential direct economic impact in 2030-40[1], $ trillion (% of total impact)	**Spillovers to upstream, downstream, and ancillary sectors** (examples)	**Shifting value chains and adapting business strategies** (examples)
Human health and performance 0.5–1.3 (35%)	Health insurance (eg, better prediction of risk and treatment outcomes) Ancillary services (eg, infrastructure required for storage and movement of cell therapies)	Spread of point-of-care diagnostics (eg, gene sequencing for cystic fibrosis) could decentralize care Pharmaceutical companies adapt business models in response to therapies that cure rather than treat over a lifetime
Agriculture, aquaculture, and food 0.8–1.2 (36%)	Food retailing and restaurants (eg, food with new properties like plant-based and cultured protein) Real estate (eg, reduction in land use because of more efficient agriculture, lab-grown meat) Transport and logistic players adjust to produce with new properties (eg, longer shelf life, ability to grow in new geographic regions) Environment (eg, meat production with smaller carbon footprint)	Transformation of meat value chain from: animals bred, fed, slaughtered, processed, and distributed → tissue sampling, media production, and live-tissue cultivation of cells into meat Consolidation of value chain as single player can do many steps in the value chain Emergence of business model selling yield goals instead of products such as bags of seed or pesticides
Consumer products and services 0.2–0.8 (19%)	Health insurance (eg, better prediction of risk based on consumer DTC genetic tests) Food (eg, change in demand driven by personalized diet plans) Healthcare (eg, DTC tests require more support from genetic counselors)	Movement up the value chain (eg, DTC testing company developing clinical products and services) New ways to monetize data (eg, companies selling consumer data to pharmaceutical companies for R&D purposes)
Materials, chemicals, and energy 0.2–0.3 (8%)	Fashion and cosmetics (eg, materials made more sustainably, such as nylon made from microbes rather than petrochemicals) Electronics (eg, biology-based optical film for displays) Consumer (eg, novel materials that improve quality of life for consumers)	Compressed value chain (eg, design, manufacturing, and customization of physical inputs in one place) Formation of platform-based companies serving clients across sectors

1. Figures may not sum to 100% because of rounding. These impact estimates include direct economic impact across arenas of innovation. They are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation. % of total impact is based on the midpoint of our estimated range of annual potential direct economic impact.

Source: McKinsey Global Institute analysis

The total economic impact will likely be larger than the direct impact of the use cases we have identified and assessed

The direct potential impact estimated across the domains may be only a small portion of the potential scale of impact. Even in the near term, the impact could be larger, as new scientific breakthroughs emerge and as the direct impact we note above starts to have knock-on effects or spills over to other sectors. More broadly, the impact could radiate out to almost every sector of the economy, with effects on society and the environment. For instance, the visible pipeline of applications we sized in the human health domain is just a fraction of the full potential: as noted, between 1 and 3 percent of the current total global burden of disease could be reduced in the next ten to 20 years from just the use cases we examined—roughly the size of eliminating the global disease burden of lung cancer, breast cancer, and prostate cancer combined. While this near-term impact is rather significant, it is only a fraction of the transformational change that may be achievable. Many factors will shape the full extent of impact and the ability to capture as much of the full potential as possible; they include funding for basic science and treatments that pass clinical trials and are commercially viable alternatives to existing therapies.

The total economic impact could be larger than our direct sizing for a number of reasons:

— **Unassessed use cases.** Our library of about 400 use cases, while extensive, is not exhaustive. We acknowledge that there are many use cases being developed in private labs or in the defense industry, where developments remain confidential for commercial or national security reasons.

— **Faster and higher adoption.** Several factors could accelerate adoption of scientific advances. Companies could help speed up time to market and adoption of some applications by working with the scientific community, for example focusing on scientific advances and technologies that are likely to have the most impact, investing in them, and partnering with innovative startups. In addition to adoption speed, adoption peaks could be higher due to factors such as shifting product features, customer preferences, and lower prices. One example of this potential is higher or faster adoption of currently expensive therapies (for instance, CAR T-cell therapy for cancer) due to broader insurance coverage or lower prices.[29]

— **Knock-on economic effects.** The impact of some applications could in turn have knock-on effects for the broader economy. For example, improved health could mean that people lead longer and more productive lives; this in turn means that retirement ages may rise, demand for eldercare delivered in the home may rise, and social security and pensions may need to adapt. Alternative proteins are another example: if they replace some meat production, land now dedicated to grazing could be repurposed for conservation efforts or new commercial uses.

— **Impacts on upstream, downstream, and ancillary players.** After a first wave of change in the domains directly affected by bio innovations, a second wave may spill over to adjacent sectors or firms, transforming value chains and encouraging new business models and players. For example, applications in agriculture, aquaculture, and food could affect food retailing. Numerous fast-food chains have announced deals with plant-based meat-substitute producers to offer vegetarian and vegan versions of popular menu items. Logistics and transportation players may adapt to genetically engineered produce being able to be kept fresh for far longer even without being refrigerated, and to increased demand for alternative proteins.

[29] CAR T-cell (chimeric antigen receptor T-cell). CAR T-cells are genetically engineered T-cells that express artificial chimeric antigen receptors on their surface. These engineered T-cells enable a patient's own immune system to identify and destroy targeted cells.

— **Existing scientific breakthroughs spur more breakthroughs.** Some innovations have the ability to generate more breakthroughs, by helping to improve existing products and processes or by inventing and implementing new ones. For example, the Human Genome Project initially set out to determine a map of the human genome. In doing so, the project was instrumental in pushing the development of high-throughput technologies for preparing, mapping, and sequencing DNA. The improved ability to sequence DNA has, in turn, led to sequencing of the genomes of microbes, plants, and animals, which has advanced many fields of science, including microbiology, virology, infectious disease, and plant biology. In addition, new biology and new technologies brought about by the Human Genome Project have enabled many other large-scale research initiatives to go forward. Examples include the Encyclopedia of DNA Elements research consortium (ENCODE), International HapMap Project, 1000 Genomes, Cancer Genome Anatomy Project, Human Microbiome Project, and Roadmap Epigenomics Project.[30]

— **More scientific breakthroughs enabling more commercial applications.** Biology research is continually developing, and scientific breakthroughs we haven't yet contemplated could provide a foundation for downstream commercial applications that may become available in the next few decades. For example, before the Human Genome Project, researchers knew the genetic basis of tens of disorders. Today, they know the basis of thousands of conditions. Genomics is thus helping transform medicine. More than 100 different drugs approved by the US Food and Drug Administration (FDA) are now packaged with instructions that tell doctors to test their patients for genetic variants linked to efficacy, dosages, or risky side effects.[31] Funding basic science or helping promising applications accelerate through research pipelines could directly influence the number of commercial applications in the future, beyond use cases we may have missed in our sizing.

In the longer term, every sector may be affected as bio innovation transforms profit pools, value chains, and business models. In the years ahead, if you are not using biology to make products, you will very likely be consuming products made that way. The impact could go much further, with biology potentially being used to address some of the great challenges of our time.

As an example, climate change is a key area in which biology could play a role. By 2040 to 2050, the direct applications we sized could reduce annual average man-made GHG emissions by 7 to 9 percent from 2018 emissions levels. This is the equivalent of up to eight times the total carbon dioxide (CO_2) emissions of the global airline industry in 2018.[32] Applications such as a shift toward bioroutes for production and alternative proteins would be important contributors to reduced emissions. The knock-on effects could alleviate pressure on cropland and reduce deforestation.

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30 Leroy Hood and Lee Rowen, "The Human Genome Project: Big science transforms biology and medicine," *Genome Medicine*, September 2013, Volume 5, Number 79; and "Spinoff projects related to the Human Genome Project," Human Genome Project Information Archive 1990–2003, https://web.ornl.gov/sci/techresources/Human_Genome/research/spinoffs.shtml. Epigenomics is the study of the epigenome, specifically epigenetic modifications that affect gene expression such as DNA methylation and histone modification. This can direct such actions as turning genes on or off, and controlling the production of proteins in particular cells.

31 Susan Young Rojahn, "A decade of advances since the Human Genome Project," *MIT Technology Review*, April 12, 2013.

32 Total GHG emissions, including from land use, land-use change, and forestry, were 75.9 $GtCO_2e$ in 2018, according to the UN's *Emissions gap report 2019*. For the purposes of policy discussion and target setting, greenhouse gases are generally quantified by global warming potential (GWP), a measure of how much energy the emissions of one ton of gas will absorb during a given period, relative to the emissions of one ton of carbon dioxide. GWP is calculated for a specific time span, most commonly 100 years. But the lifetime for each greenhouse gas is different. Methane lasts in the atmosphere only for approximately 12 years, so its GWP will differ depending on a given time span. One ton of methane has 28 times the effect of one ton of carbon dioxide when measured at a 100-year GWP but 84 times the effect at a 20-year GWP. Given the importance of action and the short-term potential gain of reducing agriculture's methane emissions, our primary analysis is based on 20-year GWP values. The global CO_2 emissions of the airline industry were about 0.9 gigaton in 2018. *ICAO global environmental trends – present and future aircraft noise and emissions*, International Civil Aviation Organization working paper number 54, May 7, 2019. Also see *Understanding global warming potentials*, US Environmental Protection Agency; and *Climate change 2013: The physical science basis*, Intergovernmental Panel on Climate Change, 2013.

Biology could also make a significant contribution to efforts to increase food security around the world, addressing hunger and malnutrition. The Bill & Melinda Gates Foundation, for example, suggests that by using improved fertilizer and more productive crops such as genetically engineered varieties, African farmers could theoretically double their yields.[33]

However, for all this potential, biological applications will not likely be a panacea for societal ills and challenges. In many ways, their societal effects proceed unevenly, in part driven by level of access to these innovations across socioeconomic groups or nations. And, critically, the risks of biology will need to be addressed and satisfactorily mitigated if biology is to realize its potential.

Bio innovation carries profound and unique risks and issues

Profound risks accompany this surge of innovation in biology. Get it right and the benefits could be significant; get it wrong and disastrous consequences could ensue at the population level. These risks introduce a unique set of considerations which, if not managed properly, could potentially outweigh the promised benefits:

— **Biology is self-replicating, is self-sustaining, and does not respect jurisdictional boundaries.** For example, new genetically engineered gene drives applied to the vectors that spread disease (mosquitoes in the case of malaria) could have enormous health benefits, but they can be difficult to control and can potentially do permanent damage to ecosystems. There are also no boundaries for the spread of unintended consequences.

— **The interconnected nature of biology can increase the potential for unintended consequences.** Biology is highly interconnected; changes to one part of a system can have cascading effects and unintended consequences across entire ecosystems or species. Examples include planting a genetically engineered crop that could result in unintended effects on the species or broader ecosystem. Gene editing could also have unintended or "off target" effects. For instance, even in successful gene editing, "off-target" mutations beyond those intended have been observed for all classes of genome editing tools used to date, including CRISPR.[34]

— **Low barriers to entry open the door to potential misuse with potentially fatal consequences.** Unlike nuclear materials, some biological technologies are relatively cheap and accessible. A thriving community of "biohackers" practices gene editing today in community labs or even at home. Commercial kits to perform CRISPR gene editing are sold on the internet. This activity might affect only the individuals biohacking their own bodies, but there are broader risks, for example if individuals are able to create and unleash a virus. Beyond such risks, we could see increased competition between companies, particularly in consumer applications, which could lead to overhyped marketing. Competition to bring biologically based products and services to market in some cases has led to commercialization before the relevant science is fully tested and established, which could mislead consumers, erode trust, or even compromise health and safety.

— **Differing value systems make it hard to forge consensus, including on life-and-death issues.** At the heart of many of these risks is the challenge of coordination across value systems—at the individual, cultural, and national levels. Technical and scientific issues, such as embryo editing, quickly become moral questions, and often, decisions are expressions of one's value system. Beyond the many risks are significant ethical questions that exceed the scope of this report. Is the ability to edit out disabilities before

[33] Elizabeth Lopatto, *Can GMOs end hunger in Africa?,* The Verge, February 2015.

[34] Yong Cheng and Shengdar Q. Tsai, "Illuminating the genome-wide activity of genome editors for safe and effective therapeutics," *Genome Biology*, December 2018, Volume 19; Dana Carroll, "Collateral damage: Benchmarking off-target effects in genome editing," *Genome Biology*, June 2019, Volume 20; and *Nature Medicine*, "Editorial: Keep off-target effects in focus," August 2018, Volume 24.

birth "playing God"? Is it acceptable to edit an embryo to prevent sickle cell anemia, but wrong to choose a baby's skin or eye color? Sustained efforts and new approaches to engagement, oversight, regulation, and safeguarding are needed to manage such risks. These will need to take into account societal norms and acceptance that are often shaped by religious, cultural, and historical values and can vary widely between countries. The challenge of cooperation and coordination of value systems across cultures and jurisdictions is no easy task, particularly when advances in these scientific domains could be seen as a unique competitive advantage for businesses or economies.

— **Privacy and consent issues are fundamental.** Concerns about personal privacy and consent are rife, given that the cornerstone of biological advances is data mined from our bodies and brains. In the United States, using the results of only 1.28 million DTC genetic tests, it was possible to access material from open databases and identify about 60 percent of Americans with European ancestry from a DNA sample as of late 2018, prompting some DTC companies to tighten up the availability of such data.[35] As applications of biomachine interfaces and, in particular, brain-machine interfaces spread, the amount of data harvested from brains will most likely increase. When and how do individuals give consent to what data are gathered and how they are used? Is the science available that can differentiate between thoughts that an individual wants and does not want to share?

— **Unequal access could perpetuate socioeconomic disparity, with potentially regressive effects.** Biological advances and their commercial applications may not be accessible to all in equal measure, thereby exacerbating socioeconomic disparity. At the country level, developments are advancing quickest and most broadly in relatively rich nations. Our analysis finds that countries with high rankings on the Institute for Health Metrics and Evaluation's (IHME) socio-demographic index account for roughly 30 percent of today's global disease burden but could gain about 70 percent of the total share of reduction in the global disease burden from bio innovations.[36] Within countries, access to some beneficial biological applications may be cost prohibitive and thus available only to the wealthy, like cellular and gene therapies today. Furthermore, the very nature of these applications to edit "less desirable" traits could lead to outcomes that are regressive and disenfranchise marginalized groups. Examples of this could include genome editing for traits related to blindness or dwarfism, which are tied to the ongoing discussion of so-called ableism—that is, whether the aim of restoring a sense inherently marginalizes communities that do not see the lack of that sense as a disability.

These risks demand a considered response and potentially new approaches. In past waves of technological change, regulation has emerged in response to innovations; in biology, there is a strong argument for a proactive approach. As far back as 1975, prominent scientists, lawyers, and medics gathered in California to draw up voluntary guidelines to ensure the safety of recombinant DNA technology.[37] The scientific communities in other fields, such as nuclear physics and AI, are also grappling with analogous issues, and there could be room for cross-disciplinary collaboration. Regulation will be important, but so too will oversight and monitoring of science even as it develops, as well as safeguards that scientists build into new biological technologies.

[35] Yaniv Erlich et al., "Identity inference of genomic data using long-range familial searches," *Science*, November 2018, Volume 362, Issue 6415.

[36] The socio-demographic index is a development classification system specific to the Institute for Health Metrics and Evaluation (IHME) based on metrics such as per capita income and average years of schooling. Figures given are based on the IHME Global Burden of Disease 2017.

[37] Recombinant DNA molecules are formed by combining genetic material from multiple sources to create sequences not found in the genome (molecular cloning, for instance). See Paul Berg et al., "Summary statement of the Asilomar Conference on recombinant DNA molecules," *Proceedings of the National Academy of Sciences*, June 1975, Volume 72, Number 6.

National responses will not be sufficient, because biology doesn't respect borders—as the world experienced firsthand with the rapid spread of the COVID-19 infection around the globe. Moreover, we can already see very different regulatory responses reflecting a world with many different value systems. Some countries take a cautious view of frontier innovation, including embryo editing and genetic engineering of food crops; others take a permissive view. Lighter-touch regulation may deliver—or be seen to deliver—competitive advantage compared with a more restrictive approach. Global cooperation and coordination could help level the playing field but will be difficult to achieve when disparate value systems exist.

Science is the starting point—applications need to be commercialized and diffused responsibly to deliver beneficial impact at scale

The journey from the lab to adoption has three broad stages—scientific research, commercialization, and diffusion—that bleed into each other in a continuous evolution. For biological applications to diffuse and deliver beneficial impact responsibly and at scale, six factors are relevant that determine whether adoption occurs and how long that takes. The first— investing in scientific research—is germane in the first stage. Four factors—value propositions, business models, go to market, and operational scalability—are key for the second and third stages, commercialization and diffusion. The sixth relates to risk and mechanisms for governing the use of applications; this is vital in all three stages:

— **Investment in scientific research.** Funding, tools, talent, and access to data are necessary and powerful elements of the investment needed to enable scientists to be successful. It tends to take years of research and sizable investment in these capabilities to get an idea to the point at which a product or service is scientifically feasible.[38] To give an idea of the financial investment needed, the Human Genome Project involved $3 billion in investment. Applications are moving along fastest in higher-income economies where investment money is available. The development of new tools and technologies in biological sciences has extended the capabilities of research. For instance, CRISPR was a major leap forward in the ability to edit genes. Expanding and ever-cheaper computing power has enabled the rapid development of bioinformatics.[39] Ensuring that sufficient numbers of skilled scientists are trained is vital. Finally, investment to ensure that scientists have access to the data on which advances depend is crucial. The development of annotated and accessible databases such as the Human Genome Project, GenBank, and UniProt has played a significant enabling role in biological advances.

— **Four factors play a role in commercialization and diffusion.** Once an application is scientifically feasible, other factors will determine the journey from lab to market to wide adoption and diffusion. We have identified four key factors, the first of which is whether a new biology-based product or service offers a value proposition to potential end users. Innovations need to compete with existing products not only on cost but also by offering higher quality or new properties or, indeed, by meeting a need not fulfilled by existing offerings. Creating a value proposition is not easy. Many potential buyers of biology-based products are in industries with low margins such as energy and agriculture, and established products or methods of production have had years to develop ways to improve efficiency. Even when they start diffusing, some biology-based innovations remain costly. Although the cost is now falling rapidly, the cost to produce the first lab-grown hamburger was more than $300,000.[40]

[38] We define scientific feasibility as experimental success in the target population (for instance, in the case of human health, success in humans rather than mice models). For applications where we could not identify proof of concept in academia or industry, we assessed feasibility using sector-specific analogs and expert interviews that estimate how far away scientific feasibility might be.

[39] This is a hybrid science that links biological data with techniques for information storage, distribution, and analysis to support multiple areas of research, including biomedicine.

[40] Neil Stephens, Alexandra E. Sexton, and Clemens Driessen, "Making sense of making meat: Key moments on the first 20 years of tissue engineering muscle to make food," *Frontiers in Sustainable Food Systems*, July 10, 2019; and Muhammad Sajid Arshad et al., "Tissue engineering approaches to develop cultured meat from cells: A mini review," *Cogent Food & Agriculture*, 2017, Volume 3, Issue 1.

— **The second factor is whether business models are suitable in what may be a fast-changing landscape, as in most waves of innovation.** New models, such as bionative companies that combine expertise in biology, chemistry, data science, and automation, may be needed. The third factor is ensuring that a new product or service effectively hits the right potential customers, with go-to-market elements, including pricing, sales, and marketing. A fourth vital factor is the ability to scale up operations; necessary aspects include having the right infrastructure, processes, supply chain, and talent. New bio-based fermentation techniques can build on considerable existing fermentation capacity, but more will be needed. Healthcare capacity will need to adapt and grow to disseminate medical innovations. For instance, with CAR T-cells now being administered to a growing number of patients in hospitals and treatment centers, sufficient infrastructure for manufacturing and delivering the cells is necessary.[41] Again, sufficient talent is needed. Genetic counselors to help patients and the public understand and interpret the results of genetic tests are already in short supply.[42] In the United States, for instance, there were approximately 5,000 certified genetic counselors in 2019.[43] Yet 26 million consumers have taken an at-home genetic test.

— **Risk and mechanisms governing use.** Given the profound and unique risks accompanying bio innovation, mechanisms governing use, including broad acceptance from society and regulation, are key both in the first stage and also as the science commercializes and diffuses. Even if an application is scientifically feasible and the economics are favorable, end users and other stakeholders must want to use it, sometimes accepting some risk. As an illustration, it took nearly 20 years from the production of the first strain of Golden Rice—fortified with vitamin A—to be approved for use in 2019 in the Philippines, the first country with many people suffering from vitamin A deficiency to approve Golden Rice.[44] Regulators delayed in the face of persistent opposition to GMOs.[45] Our research finds that about 70 percent of the total potential impact could hinge on consumer, societal, and regulatory acceptance, based on an analysis of areas where regulations exist today in major economies.[46]

The pace and extent of adoption of bio innovations vary significantly depending on the application

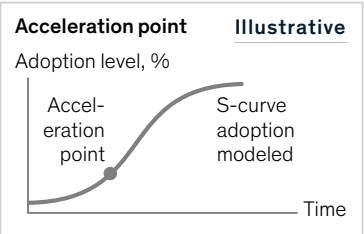
The pace and extent of adoption will vary enormously depending on the application and the domain (Exhibit E6). Some applications, including using new bioroutes to manufacture drugs, are already showing robust signs of early commercial adoption. Others such as CAR T-cell therapy for cancer have recently become commercially viable at the time of writing in 2020, meaning adoption is at an early stage and could increase rapidly over the coming decade. Still others, such as using genetically engineered plants to sequester CO_2, show promise in scientific research, but commercial viability and adoption by farmers or other buyers are likely further out.

41 Jacob Bell, *Car-T ups challenges in pharma supply chain*, Biopharma Dive, April 23, 2018.
42 J. M. Hoskovec et al., "Projecting the supply and demand for certified genetic counselors: A workforce study," *Journal of Genetic Counseling*, February 2018, Volume 1.
43 *Genetic counselor workforce initiatives*, National Society of Genetic Counselors.
44 Prior to approval in Philippines, Golden Rice was registered as safe in Australia, Canada, New Zealand, and the United States, all countries with few vitamin A deficiency problems. See Michael Le Page, "GM golden rice gets landmark safety approval in the Philippines," *New Scientist*, December 31, 2019. This is based on World Health Organization data on the prevalence of vitamin-A deficiency in pregnant women and preschool-age children from 1995 to 2005. See WHO, *Global prevalence of vitamin A deficiency in populations at risk 1995–2005*, WHO Global Database on Vitamin A Deficiency, 2009.
45 Jesse Hirsch, "Golden Rice: A brief timeline of the world's most controversial grain," *Modern Farmer*, August 27, 2013; *Philippines approves nutritionally-enhanced GMO Golden Rice for human consumption*, Genetic Literacy Project, December 18, 2019.
46 We examined existing regulations and their applicability to sized applications. Applications were also considered at stake if they relate to highly sensitive topics in academic circles, such as embryo editing and bioweapons. Our analysis is as of September 2019.

Exhibit E6

Among applications assessed, adoption timing varies.

Example use cases Not exhaustive	Estimated time horizon of acceleration point of use cases across domains The acceleration point is when adoption starts to experience rapid growth[1] **Existing** Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
Human health and performance[2]	Carrier screening Noninvasive prenatal testing	CAR T-cell therapies for liquid tumors Liquid biopsy	Gene drives to reduce vector-borne diseases CAR T-cell therapies for solid tumors	Transplantable organs produced from stem cells Embryo editing for medical purposes (eg, via CRISPR)
Agriculture, aquaculture, and food[3]	Marker-assisted breeding (crops and animals used for food) Genetic tracing of food origin, safety, and authenticity (eg, allergens, species, pathogens)	Plant-based proteins Crop microbiome diagnostics and probiotic treatments	Cultured meat Genetically engineered animals—faster growth	Genetically engineered crops—faster growth through enhanced photosynthesis
Consumer products and services[4]	DTC genetic testing—ancestry	Personalized meal services based on genetic and microbiome profile DTC genetic testing—personal insights about health and lifestyle	Biosensors for monitoring of personal health, nutrition, and fitness based on omics data	Gene therapy—skin aging
Materials, chemicals, and energy[5]	New bioroutes for drug manufacturing (eg, peptides)	Novel materials—biopesticides/ biofertilizers (eg, RNAi pesticides) Improved existing fermentation processes—food and feed ingredients (eg, amino acids, organic acids)	Novel materials—biopolymers (eg, PLA, PET)	Biosolar cells and biobatteries
Other applications	DNA sequencing for forensics		Biosequestration of CO_2 Bioremediation for pollution	



1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.
2. Applications in the human health and performance domain include innovations to reduce disease burden at the individual and population levels, anti-aging treatments that extend life span, reproductive health (eg, carrier screening) applications, and innovations in drug development and manufacturing. See chapter 6.1 for the full list of applications that we sized in this domain.
3. Applications in the agriculture, aquaculture, and food domain include applications related to plants and animals for food purposes, food production, food transportation, and food storage. See chapter 6.2 for the full list of applications that we sized in this domain.
4. Applications in the consumer products and services domain include direct-to-consumer genetic testing, beauty and personal care, wellness (eg, fitness), and pets. We categorize wellness, nutrition, and fitness under consumer rather than health, because they do not directly alleviate the global disease burden or are elective or for adult enhancement, such as hair loss or cosmetics. While some of these applications could have indirect impact on the disease burden, such as fitness wearables, they are not direct treatments or therapies. See chapter 6.3 for the full list of applications that we sized in this domain.
5. Applications in the materials, chemicals, and energy domain include innovations related to production of materials (eg, improved fermentation process, new bio-routes, or novel materials), and energy production and storage. See chapter 6.4 for the full list of applications that we sized in this domain.

Source: McKinsey Global Institute analysis

Innovators, businesses, governments, and individuals need to strike a balance that enables potential to be captured while managing risks

Innovators, businesses, governments, and individuals need to become literate in biology, cognizant of the benefits of innovations as well as their risks, and how to strike the right balance between the two. The choices made today, and in the years ahead, will influence not only the path of biological science, but also the size and scope of its benefits for economies, societies, and the planet.

— **Innovators.** The scientists and researchers pioneering biological breakthroughs, and the developers and innovators who turn feasible science into commercially viable products, need to consider the opportunities and risks associated with their work. Peer review is a powerful internal governing mechanism to ensure that research is accurate and well grounded, but scientists cannot operate in a vacuum. Rather, they need to play a consistent and effective oversight role. They have a long track record of doing so. In 1975, prominent scientists, lawyers, and medical professionals gathered at the Asilomar Conference in California to draw up voluntary guidelines to ensure the safety of recombinant DNA technology, for instance.[47]

— **Businesses.** Businesses should consider how to take advantage of bio innovation, including adapting strategies. Companies operating in virtually every sector of the economy could be affected by bio innovations as applications in one domain have knock-on effects on upstream, downstream and adjacent sectors. In the case of applications in agriculture, aquaculture, and food, there will be spillover into food retailing and transportation, for instance. Moreover, entire value chains could be transformed. In the case of materials, for instance, with a shift from plastic to bio-based plastic packaging increasingly desired by consumers, the packaging industry could look very different. The meat value chain is another case in point. In the traditional meat production value chain, animals are bred, fed, slaughtered (fished), and processed prior to distribution, while the value chain for cultured meat is highly compressed, involving only tissue sampling, media production, and live-tissue cultivation of cells into meat—often done by the same company (Exhibit E7).[48]

  Many companies will likely need to adapt their business strategies. Given the uncertainty and evidently varied timing of adoption for different applications, companies should consider a portfolio-based approach toward investments in bio innovation that embraces applications that could become commercially viable in the relatively short term, and those that could deliver impact further out. By its nature, bio innovation is cross-discipline—embracing not only biological science, but also computing, AI, data analytics, and engineering. As such, it is unlikely that any business existing today can go it alone. Therefore, it's important to master the confluence of disciplines in bio innovation with the right mix of talent and collaborations. Although large companies could develop the full range of necessary capabilities in-house, it is likely to be quicker and more effective to "buy in" what they need through mergers and acquisitions, and partnerships. Small companies specializing in particular scientific fields are already collaborating with large incumbents with the market clout to commercialize at scale. As in the Digital Revolution, companies interested in the opportunity of bio innovation should consider platform-based business models that can seize cross-sector opportunities, reduce marginal costs, and drive combinatorial innovation by leveraging growing biological data. There are already platforms that offer farm-management systems and cloud-based platforms that analyze huge amounts of genomic data to inform breeding decisions.[49] Among other aspects

[47] Recombinant DNA molecules are formed by combining genetic material from multiple sources to create sequences not found in the genome (molecular cloning, for instance). See Paul Berg et al., "Summary statement of the Asilomar Conference on recombinant DNA molecules," *Proceedings of the National Academy of Sciences*, June 1975, Volume 72, Number 6.

[48] Cultured meat is produced by the in vitro cultivation of animal cells.

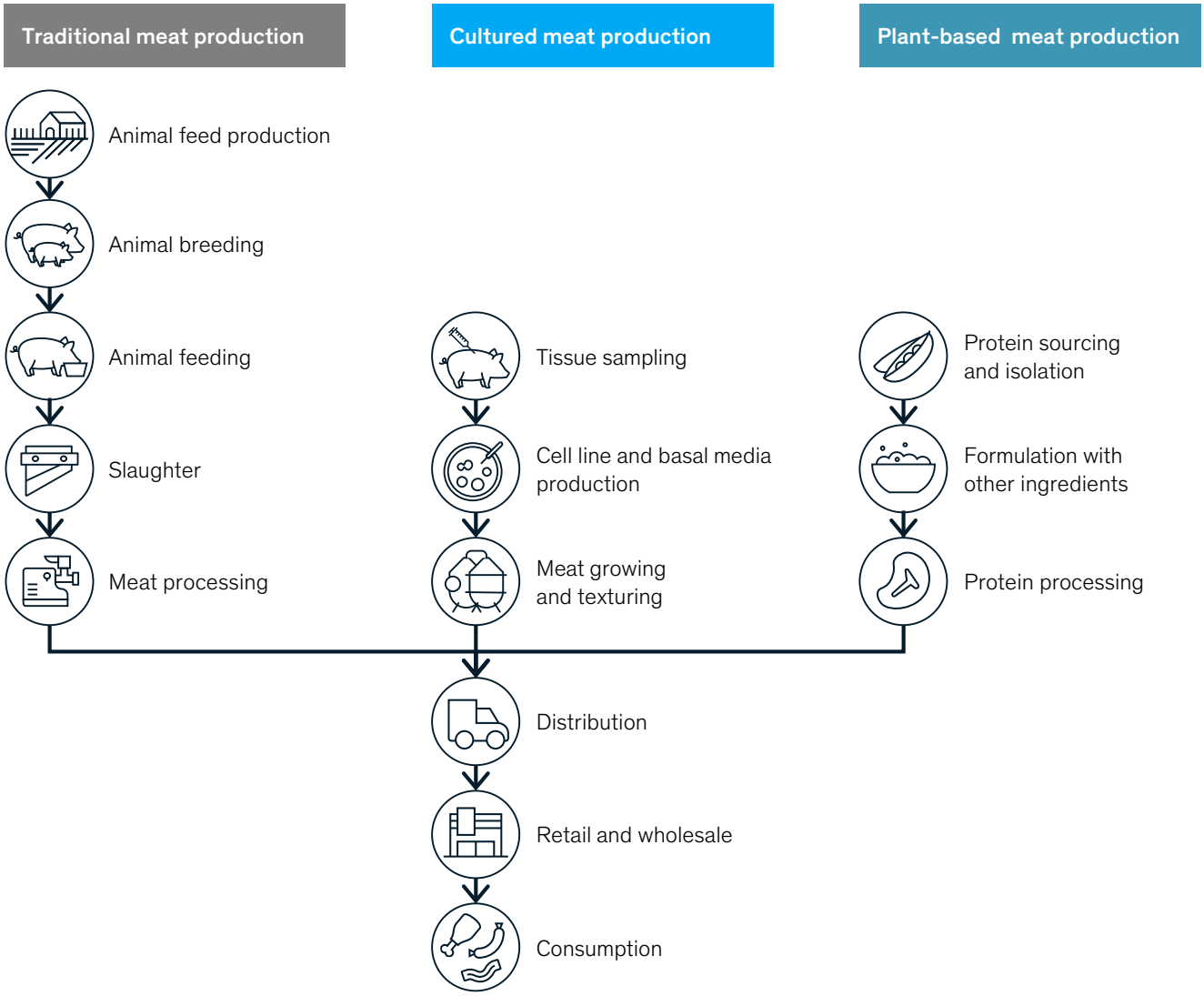
[49] Geoffrey Carr, "Factory fresh," *Economist Technology Quarterly: The Future of Agriculture*, June 2016; and BASF and NRGene, *BASF and NRGene collaborate to accelerate crop breeding*, October 29, 2019.

to consider are the range of opportunities for more personalized and precise offerings enabled by growing amounts of biological data, and innovative revenue models that could help accelerate diffusion. Subscription-based offerings to generate revenue are becoming more common in personalized products and services based on genome and microbiome profiles.

Exhibit E7

The meat value chain is shifting.

Traditional meat production vs cultured meat and plant-based meat production



Source: McKinsey Global Institute analysis

— **Civil society, governments, and policy makers need to inform themselves about biological advances and to provide thoughtful guidance.** Several governments, including those of China, the United Kingdom, and the United States, published strategic plans and goals intended to catalyze innovation and capture its benefits. However, innovation needs to be balanced by mechanisms to govern use and misuse; whether existing professional and regulatory mechanisms are fit for purpose must be considered. This analysis suggests that in the next decade, more than 50 percent of the total potential impact could hinge on consumer, societal, and regulatory acceptance, rising to about

70 percent over the next two decades.[50] Effective mechanisms to govern use, such as societal norms or regulations, will be needed to persuade society that innovations that bring benefits but may be risky and cause discomfort are being pursued safely. Today, policies to govern use vary significantly among countries with different value systems. Cross-jurisdictional cooperation is not extensive, as observed in the largely national (and subnational) responses in spring 2020 to the COVID-19 pandemic.

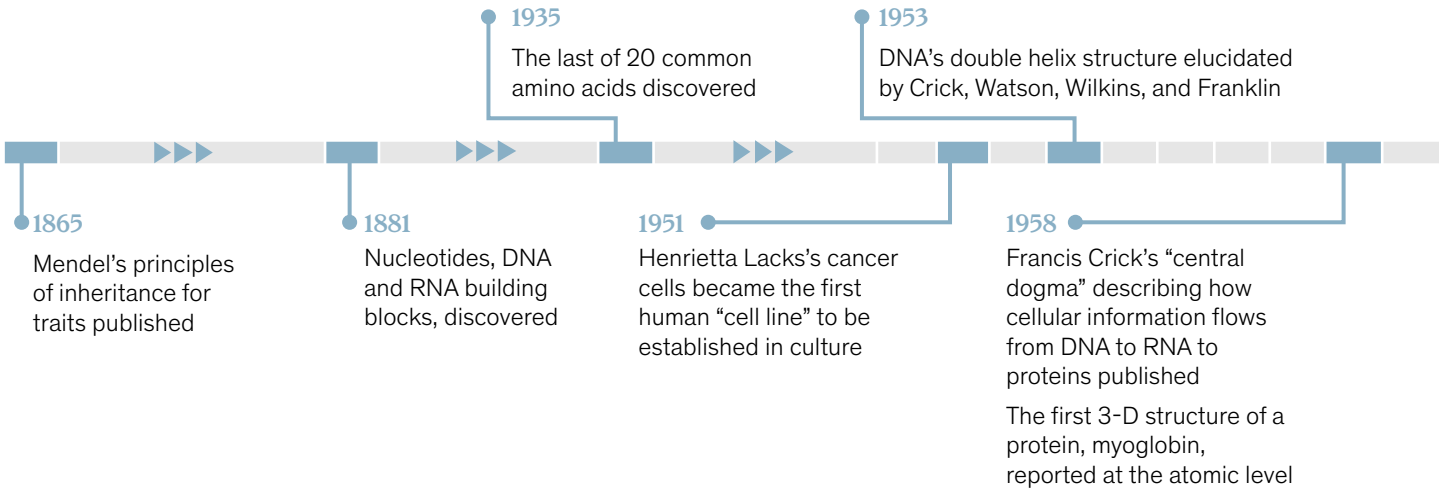
— **Individuals and consumers may be pivotal to the adoption path of biological advances.** As observed, individual attitudes toward different types of bio innovation can shape the public dialogue, societal norms, regulation, and therefore the pace and extent of adoption. To contribute effectively to what can be controversial debates (consider embryo editing as an example), individuals need to seek to understand the benefits versus the risks. They also need to appreciate that there are personal trade-offs. DTC testing, for instance, provides individuals with potentially valuable insights into the probability of contracting certain diseases, but mining that information may compromise their privacy.

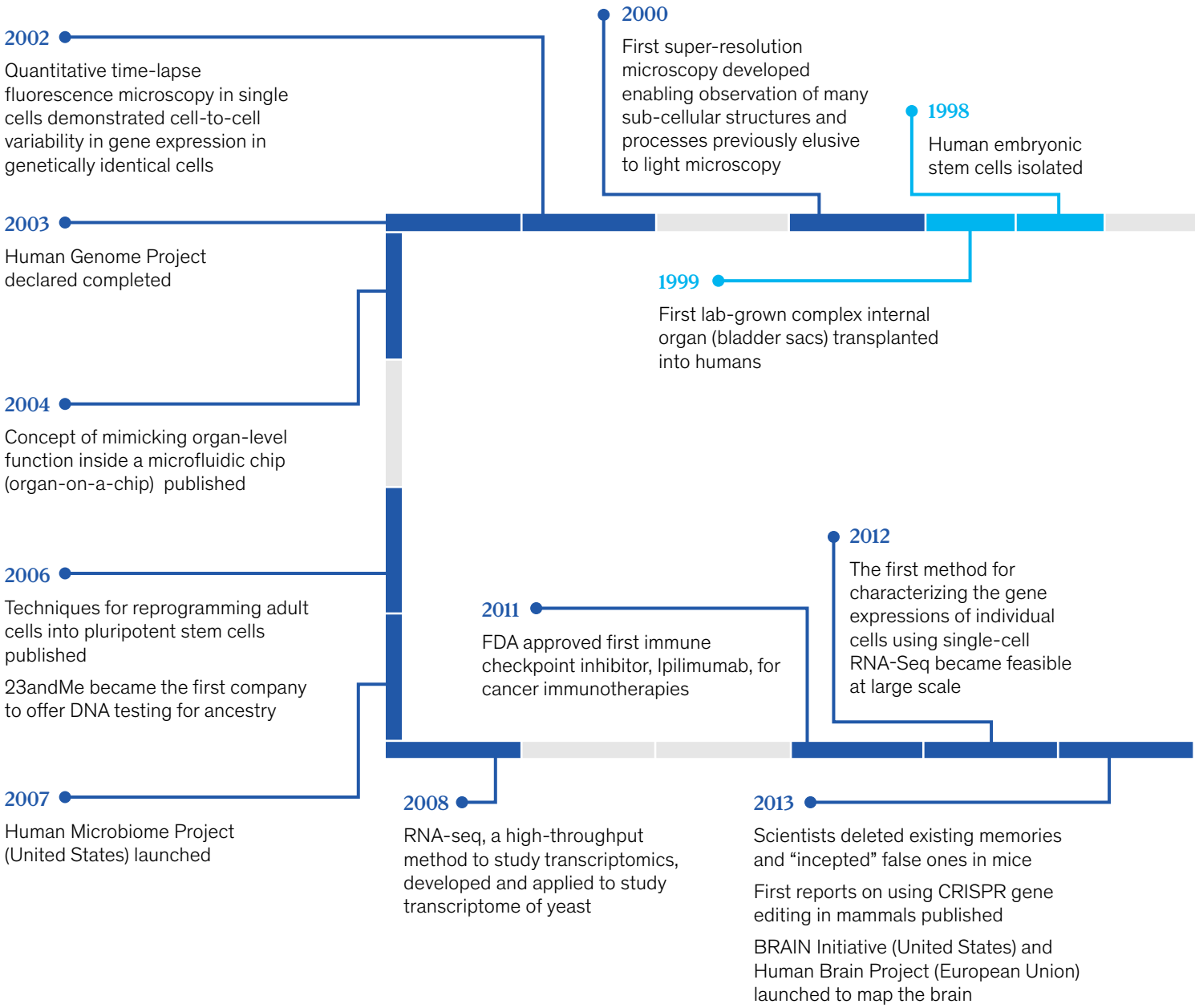
The current wave of innovation in biological sciences, combined with advances in data, analytics, and digitization, has been decades in the making. It builds on 50 years or more of scientific breakthroughs (see illustration, "A partial timeline of accelerating breakthroughs in biological sciences"). The Bio Revolution goes far beyond treating disease and into virtually every sector of the economy. Scientists in conjunction with forward-thinking companies are now harnessing the power of nature to solve pressing problems in medicine and agriculture, and, in some areas, forging innovative solutions that could mitigate pressure on the environment and help tackle climate change. The serious, and potentially irreversible, risks inherent in biology need to be fully acknowledged and directly addressed. The choices stakeholders make today and in the years ahead will determine whether what is shaping up as a Bio Revolution delivers on its considerable promise—and in a way that is safe and equitable for humanity and sustainable for the planet.

[50] Analysis includes examination of existing regulations in the different countries and their applicability to sized applications. Applications are also considered at stake if they are related to highly sensitive topics in academic circles, such as embryo editing and bioweapons. Analysis of existing regulations as of September 2019.

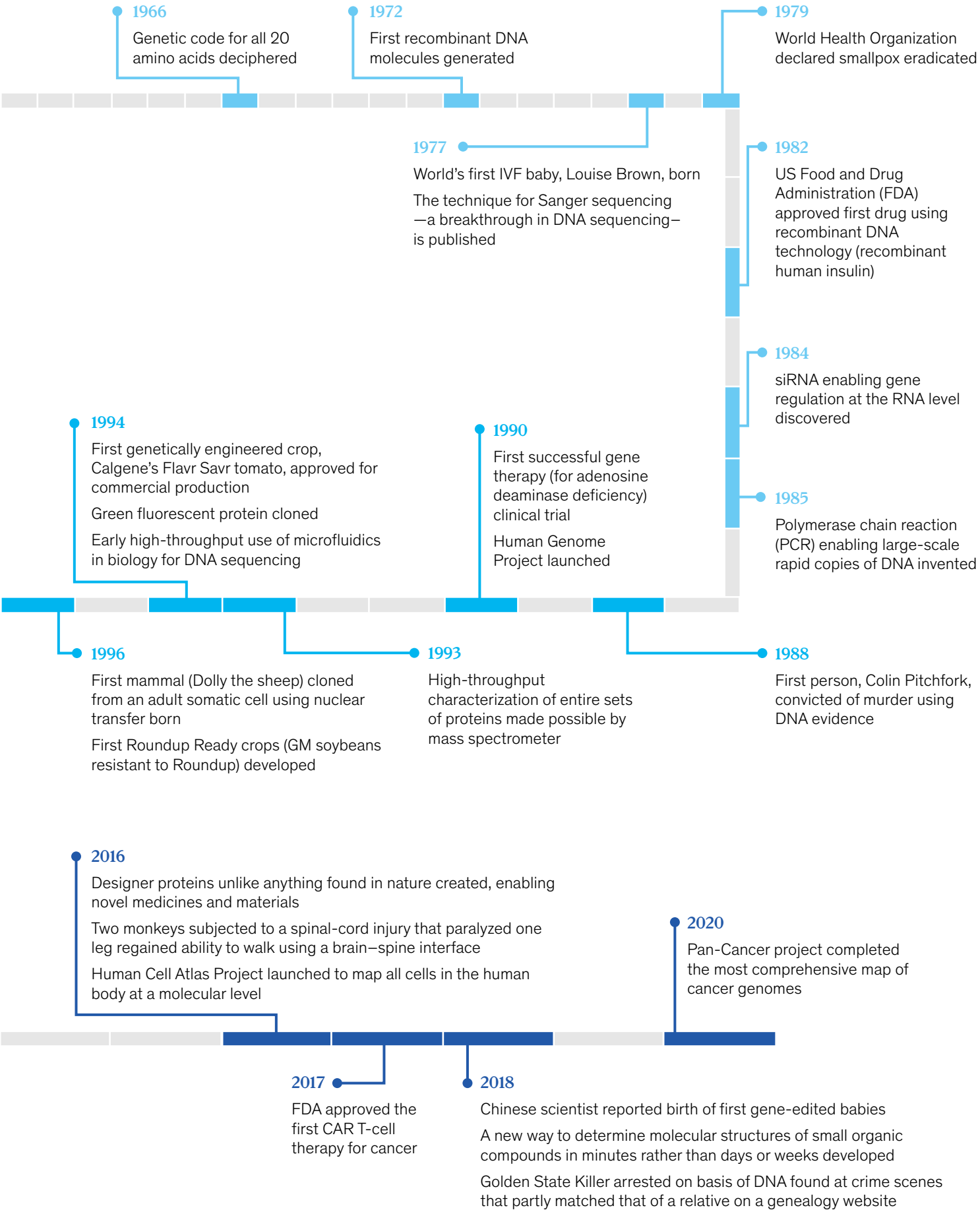
A partial timeline of accelerating breakthroughs in biological sciences

(continued on next page)


1865
Mendel's principles of inheritance for traits published
1881
Nucleotides, DNA and RNA building blocks, discovered
1935
The last of 20 common amino acids discovered
1951
Henrietta Lacks's cancer cells became the first human "cell line" to be established in culture
1953
DNA's double helix structure elucidated by Crick, Watson, Wilkins, and Franklin
1958
Francis Crick's "central dogma" describing how cellular information flows from DNA to RNA to proteins published
The first 3-D structure of a protein, myoglobin, reported at the atomic level


2000
First super-resolution microscopy developed enabling observation of many sub-cellular structures and processes previously elusive to light microscopy
2002
Quantitative time-lapse fluorescence microscopy in single cells demonstrated cell-to-cell variability in gene expression in genetically identical cells
1998
Human embryonic stem cells isolated
2003
Human Genome Project declared completed
1999
First lab-grown complex internal organ (bladder sacs) transplanted into humans
2004
Concept of mimicking organ-level function inside a microfluidic chip (organ-on-a-chip) published
2012
The first method for characterizing the gene expressions of individual cells using single-cell RNA-Seq became feasible at large scale
2006
Techniques for reprogramming adult cells into pluripotent stem cells published
23andMe became the first company to offer DNA testing for ancestry
2011
FDA approved first immune checkpoint inhibitor, Ipilimumab, for cancer immunotherapies
2007
Human Microbiome Project (United States) launched
2008
RNA-seq, a high-throughput method to study transcriptomics, developed and applied to study transcriptome of yeast
2013
Scientists deleted existing memories and "incepted" false ones in mice
First reports on using CRISPR gene editing in mammals published
BRAIN Initiative (United States) and Human Brain Project (European Union) launched to map the brain

McKinsey Global Institute


1966
Genetic code for all 20 amino acids deciphered
1972
First recombinant DNA molecules generated
1979
World Health Organization declared smallpox eradicated
1977
World's first IVF baby, Louise Brown, born
The technique for Sanger sequencing —a breakthrough in DNA sequencing– is published
1982
US Food and Drug Administration (FDA) approved first drug using recombinant DNA technology (recombinant human insulin)
1984
siRNA enabling gene regulation at the RNA level discovered
1994
First genetically engineered crop, Calgene's Flavr Savr tomato, approved for commercial production
Green fluorescent protein cloned
Early high-throughput use of microfluidics in biology for DNA sequencing
1990
First successful gene therapy (for adenosine deaminase deficiency) clinical trial
Human Genome Project launched
1985
Polymerase chain reaction (PCR) enabling large-scale rapid copies of DNA invented
1996
First mammal (Dolly the sheep) cloned from an adult somatic cell using nuclear transfer born
First Roundup Ready crops (GM soybeans resistant to Roundup) developed
1993
High-throughput characterization of entire sets of proteins made possible by mass spectrometer
1988
First person, Colin Pitchfork, convicted of murder using DNA evidence
2016
Designer proteins unlike anything found in nature created, enabling novel medicines and materials
Two monkeys subjected to a spinal-cord injury that paralyzed one leg regained ability to walk using a brain–spine interface
Human Cell Atlas Project launched to map all cells in the human body at a molecular level
2020
Pan-Cancer project completed the most comprehensive map of cancer genomes
2017
FDA approved the first CAR T-cell therapy for cancer
2018
Chinese scientist reported birth of first gene-edited babies
A new way to determine molecular structures of small organic compounds in minutes rather than days or weeks developed
Golden State Killer arrested on basis of DNA found at crime scenes that partly matched that of a relative on a genealogy website

Box E1

An April 2020 snapshot of early contributions by bio innovations in the fight against COVID-19

The rapid spread around the world in spring 2020 of a new coronavirus—SARS-CoV-2—imposed heavy health and economic costs.[1] While the impact of COVID-19 was still unfolding at the time of writing in April 2020, bio innovations had been deployed to aid the response. More needs to be done to cope effectively with pandemics of this nature, but here we share a snapshot of some of the contributions made by advances in biological science that we observed in the early days of this pandemic.

Identification. The full genome of SARS-CoV-2 was sequenced and published weeks after the novel coronavirus was identified. By comparison, it took several months to sequence and publish the SARS-CoV-1 virus that caused the SARS outbreak.[2]

Diagnosis. Advances in nucleic acid-based diagnostics have enabled more effective diagnosis. In the past decade, for instance, the continued miniaturization of reverse transcription polymerase chain reaction (RT-PCR) machines made the technology more accessible for use in the field.[3] The speed of the diagnostics also significantly improved with some labs able to produce results in 15 minutes.[4] However, the many challenges with diagnosis during the COVID-19 crisis also highlighted the fact that ample room remains for further improvement of diagnostics.

Vaccines. The speed and scale at which researchers launched efforts to develop a COVID-19 vaccine was remarkable. This agility was driven in large part by the public health urgency, but also reflected innovations such as faster and more versatile, nucleic-acid-based vaccine production and AI-powered R&D.[5] As of April 2020—around three months after SARS-CoV-2 was sequenced—more than 60 vaccines were in the preclinical stage and seven were in Phase 1 trials, although whether these efforts prove successful remained unclear. In contrast, it took more than a year after the Zika epidemic began in 2015 to start Phase 1 trials.[6]

Treatment. New capabilities assisted in developing new treatments for those infected. Genetically engineered animals were used to develop potential therapies, including using mice to produce monoclonal antibodies and cows to produce polyclonal antibodies.[7] Therapies using siRNA, RNAi, T-cells, and stem cells were also explored. Patient gene expression (mRNA) profiles were gathered into a biobank with the aim of using the repository to identify new therapies.[8] The efficacy of such treatments remained to be proven as of April 2020.

Epidemiology. Genomics was used to try to uncover population-level insights. In the case of SARS-CoV-2, its genome was regularly sequenced in different geographies and hotspots to look for mutations that could indicate its place of origin and transmission dynamics.[9]

More clearly needs to be done to improve our collective response to dangerous pandemics such as COVID-19. Bio innovations are ongoing, and the way we respond to future pandemics may look very different. For instance, in the future it may be possible to leverage emerging technologies such as AI-enabled epidemiology to predict outbreaks or use algorithms to predict the structure of proteins to enable faster drug discovery.[10]

1 Kevin Sneader and Shubham Singhal, *Beyond coronavirus: The path to the next normal*, McKinsey & Company, March 2020; and Sven Smit, Martin Hirt, Kevin Buehler, Susan Lund, Ezra Greenberg, and Arvind Govindarajan, *Safeguarding our lives and our livelihoods: The imperative of our time*, McKinsey & Company, March 2020.

2 WHO Timeline – COVID-19, www.who.int/news-room/detail/27-04-2020-who-timeline---covid-19; and Severe Acute Respiratory Syndrome (SARS), notice, Centers for Disease Control and Prevention, www.cdc.gov/sars/lab/sequence.html.

3 RT-PCR is a laboratory technique used to make large-scale copies of specific segments of DNA molecules rapidly and precisely outside the body from a mixture of DNA molecules.

4 Jim Daley, "Here's how coronavirus tests work—and who offers them," *Scientific American*, March 27, 2020, updated April 6, 2020.

5 Nicole Lurie et al., "Developing COVID-19 vaccines at pandemic speed," *New England Journal of Medicine*, March 30, 2020, updated April 6, 2020.

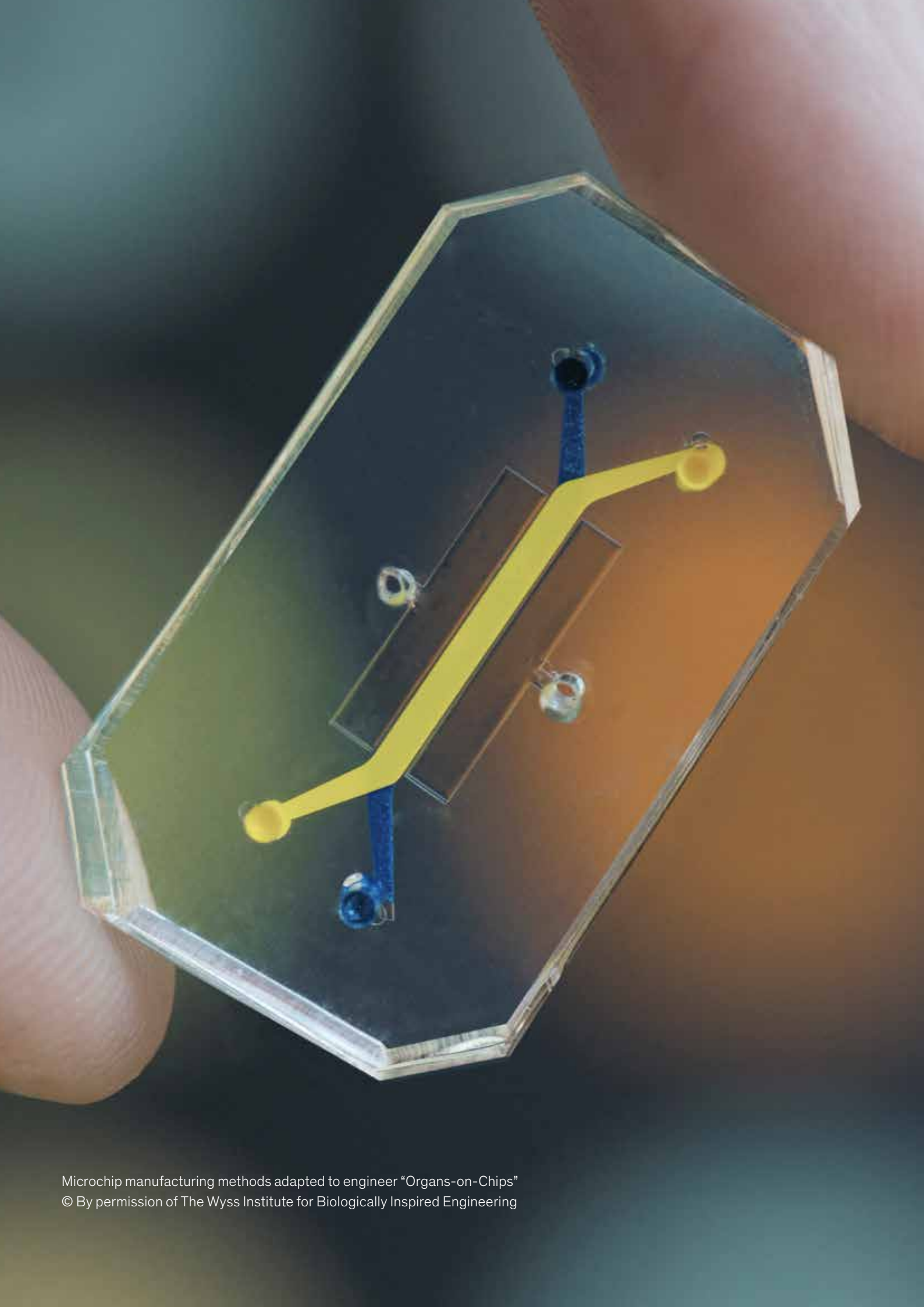
6 Alan D. T. Barrett, "Current status of Zika vaccine development: Zika vaccines advance into clinical evaluation," *NPJ Vaccines*, June 2018, Volume 3.

7 Monoclonal antibodies are man-made antibodies of predetermined specificity against targets made by identical immune cells derived from a unique parent cell.

8 Small interfering RNA or siRNA is central to RNA interference. siRNA is a family of double-stranded non-coding RNA molecules, with typical lengths of 20 to 25 base pairs that regulate the expression of specific genes with complementary nucleotide sequences by degrading their mRNA transcripts, preventing translation. RNA interference (RNAi) is an evolutionarily conserved gene silencing technique in which specific genes can be regulated and suppressed at the RNA level. T-cells are lymphocyte immune cells that protect the body from pathogens and cancer cells.

9 Niema Moshiri, *Here's how scientists are tracking the genetic evolution of COVID-19*, The Conversation, April 6, 2020.

10 One company is using a computer program to predict the 3D shape of proteins based on that protein's amino acids. Predicting the structure makes it easier to design drug molecules that are more likely to bind to the protein. See Faris Gulamali, *AlphaFold algorithm predicts COVID-19 protein structures*, InfoQ, March 31, 2020.



Microchip manufacturing methods adapted to engineer “Organs-on-Chips”
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1. A revolution in biological sciences

Imagine a world in which it is possible to produce most meat synthetically without rearing animals, paralyzed patients can have their spinal cords restored with the help of stem cells, industrial chemicals are produced in factories that use microbes, diseases caused by genetics are prevented before birth, diets and fitness regimens tailored to individual genomes and microbiomes help extend life expectancy, and biomachine interfaces enable direct mental control of electronics. The foundational technologies for all of these possibilities are already in place.

A number of advances contribute to a real sense of momentum. The Human Genome Project that mapped the entire human genome was an important foundational element, but its promise truly started to materialize as sequencing DNA became cheaper and faster. Genome sequencing has grown ever more precise—it is now possible to sequence single cells, which gives researchers and physicians the ability to assess mutations and malignancies at an unprecedented level of detail.[51] The CRISPR tool edits genes many times faster than previous techniques and with greater precision. Stem cell research is another frontier where there are significant advances.

All of these innovations are evidence of a new era that integrates biology, computing, and engineering. Indeed, these breakthroughs come on the heels of—and owe much to—advances in other technologies and disciplines, including physics, chemistry, statistics, and more. The production of biological data has also exploded, with worldwide DNA sequencing alone generating massive volumes of biological data each year.[52] Declining computing costs have made it increasingly economically viable to store, manipulate, and interpret this data on a massive scale. These different types of technology are interacting powerfully with each other—and are all falling in cost. The boom in biological data is likely to strengthen because of advances in machine learning, AI, and bioinformatics.

These technologies are interacting and reinforcing one another, and the lines between them are becoming blurred. Many applications of current and developing biological science will use more than one scientific discipline. Scientific advances under way will enable an unprecedented level of personalization and precision in products and services across sectors. The science now exists that supports tailoring products and treatments to an individual's genetic predisposition, real-time molecular measurement, and even thoughts captured as neural signals.

In this chapter, we describe the confluence of scientific advances underpinned by developments in molecular biology, computing, and data processing. Various streams of research are proceeding at different paces, and the time it takes for them to reach the point where uses can be commercialized will also differ substantially. Taken in the round, ongoing advances in the understanding of biology and the ability to measure, map, control, and create biological functions from single biomolecules to entire organisms amount to a revolution in biological sciences.

[51] Genome sequencing is a process for determining the order of DNA nucleotides within a DNA sequence. Nucleotides are the chemical compounds that are the basic structural units of RNA and DNA.

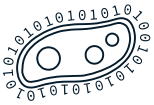
[52] Erika Check Hayden, "Genome researchers raise alarm over big data," *Nature*, July 1, 2015.

Bio innovation is occurring in four arenas

Several trends in science and technology are powering human understanding of biological processes and enabling us to engineer them for myriad uses. Innovations cover a wide range of interdisciplinary fields in four key arenas: biomolecules, biosystems, biomachine interfaces, and biocomputing. Major breakthroughs in each are reinforcing one another (Exhibit 1).
The bio innovations described in this report build on an extensive foundation of pioneering research that has enabled innovation to develop in these four arenas.

Exhibit 1

Bio innovation is occurring in four key arenas.



	Biomolecules	Biosystems	Biomachine interfaces	Biocomputing
Definitions				
Mapping	Cellular processes and functions via measuring intracellular molecules (eg, DNA, RNA, proteins) in the study of omics	Complex biological organizations and processes, and interactions between cells	The structure and function of nervous systems of living organisms	Intracellular pathways or networks of cells to return outputs based on specific conditions (for computation)
Engineering[1]	Intracellular molecules (eg, via genome editing)	Cells, tissues, and organs, including stem cell technologies and transplantation	Hybrid systems that connect nervous systems of living organisms to machines	Cells and cellular components for computational processes (storing, retrieving, processing data)
Examples	Gene therapy for monogenic diseases	Cultured meat grown in a lab	Neuroprosthetics for motor control (implant or external headset) of human or robotic limb	Data storage in strands of DNA

1. Design, de novo synthesis, or modification.
Source: McKinsey Global Institute analysis

Of the four, innovators are most active in the field of biomolecules, which is developing the fastest judging by the number of active startups and amount of funding.[53] Biosystems, which is closely related to biomolecules, is the second-most-active area.[54] Biomachine interfaces, or connecting nervous systems to machines, are at a relatively early stage, but activity is increasing among established technology companies, academic research labs, and emerging startups.[55] Biocomputing is arguably the least developed of the four key arenas. [56]

Biomolecules

This area groups biological sciences that are collectively known as omics and molecular technologies (see Box 1, "The full range of omics and molecular technologies"). Omics consist primarily of mapping and measuring various molecules and pathways within cells. Molecular technologies engineer such molecules and pathways.

Of all the omics, genomics is the most technologically advanced; applications that measure and map genes and then engineer them are in full development and use. However, the genome is by no means the entire story; other omics—particularly epigenomics—are needed to understand phenotypes (characteristics that manifest) by studying a number of steps such as what genes are expressed, at what level, and what environmental factors have an influence.[57] While the genome is largely static, other omics are dynamic and vary across time and in different environments. Work on these other omics is increasing. In particular, analysis and engineering of RNA (transcriptomics) and proteins (proteomics) are accelerating.[58] The science behind each omic varies in maturity, and accordingly, the amount of funding and the volume of publications in each area vary widely (Exhibit 3).

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53 In the area of biomolecules, see, on the Human Genome Project, International Human Genome Sequencing Consortium, "Finishing the euchromatic sequence of the human genome," *Nature*, October 2004, Volume 431, Number 7011. On the introduction of pluripotent stem cells, see Kazutoshi Takahashi and Shinya Yamanaka, "Induction of pluripotent stem cells from mouse embryonic and adult fibroblast cultures by defined factors," *Cell*, August 2006, Volume 126, Number 4. On RNA-seq, see Ali Mortazavi et al., "Mapping and quantifying mammalian transcriptomes by RNA-Seq," *Nature Methods*, July 2008, Volume 5, Number 7; and Tamar Hashimshony et al., "CEL-Seq, single-cell RNA-Seq by multiplexed linear amplification," *Cell Reports*, September 2012, Volume 2, Number 3. In the case of CRISPR, three papers are worth highlighting: Martin Jinek et al., "A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity," *Science*, August 2012, Volume 337, Number 6096; Le Cong et al., "Multiplex genome engineering using CRISPR/Cas systems," *Science*, February 2013, Volume 339, Number 6121; and Prashant Mali et al., "RNA-guided human genome engineering via Cas9," *Science,* February 2013, Volume 339, Number 6121. For CAR T, see James N. Kochenderfer et al., "Adoptive transfer of syngeneic T-cells transduced with a chimeric antigen receptor that recognizes murine CD19 can eradicate lymphoma and normal B cells," *Blood*, November 2019, Volume 116, Number 19.

54 In biosystems, key papers cover, for instance, organ-on-a-chip technology. See Kwanchanok Viravaidya, Aaron Sin, and Michael L. Shuler, "Development of a microscale cell culture analog to probe naphthalene toxicity," *Biotechnology Progress*, January–February 2004, Volume 20, Number 1. On the Human Microbiome Project, see Peter J. Turnbaugh et al., "The Human MicroBiome Project," *Nature*, October 17, 2007. For the Human Brain Project and the BRAIN Initiative, see Henry Markram et al., "Introducing the Human Brain Project," *Procedia Computer Science*, 2011, Volume 7; and Thomas R. Insel, Story C. Landis, and Francis S. Collins, "The NIH BRAIN initiative," *Science*, May 2013, Volume 340, Number 6133. On the Human Cell Atlas, see Aviv Regev et al., "Science forum: The Human Cell Atlas," *eLife*, 2017.

55 In biomachine interfaces, on reconstructing vision from fMRI activity, see Shinji Nishimoto et al., "Reconstructing visual experiences from brain activity evoked by natural movies," *Current Biology*, October 2011, Volume 21, Number 19. On implanted human neuroprosthetic arms, see Max Ortiz-Catalan, Bo Häkansson, and Rickard Branemark, "An osseointegrated human-machine gateway for long-term sensory feedback and motor control of artificial limbs," *Science Translational Medicine*, October 2014, Volume 6, Number 257. For a key paper on brain-spine interfaces in monkeys, see M. Capogrosso et al., "A brain–spine interface alleviating gait deficits after spinal cord injury in primates," *Nature*, November 2016, Volume 539, Number 7628.

56 In biocomputing, a key paper relating to automated DNA data storage is Christopher N. Takahashi et al., "Demonstration of end-to-end automation of DNA data storage," *Scientific Reports*, March 2019, Volume 9, Number 4998.

57 A phenotype is an organism's observable characteristics that could be influenced both by the genes of the organism and the environment. The genotype is expressed when the information encoded in genes' DNA is used to make protein and RNA molecules. The expression of the genotype contributes to the individual's observable traits—the phenotype. An allele is any of the alternative forms of a gene that may occur at a given locus.

58 Transcriptomics is the comprehensive identification and quantification of the complete set of RNA transcripts of a biological system (such as the human gut or skin, and in the soil around farms) at a specific point in time. Proteomics is the comprehensive identification and quantification of the complete set of proteins of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time.

Box 1

The full range of omics and molecular technologies

Omics is a collective name for a number of scientific research streams that collectively map and measure biological molecules in a particular "ome." In this research, we also include technologies for the engineering of biological molecules (Exhibit 2). The first set of omes corresponds to the central dogma of molecular biology in which genes are transcribed into RNA and then translated into proteins.

Genomics. This is the study of genes and their functions and of techniques related to them. The genome consists of the full genetic complement of an organism; its DNA is composed of building blocks called nucleotides. Genotyping is the process of determining the genetic makeup of an individual by examining the DNA sequence. An organism's genotype is the sets of genes it carries, while a phenotype is all of an organism's observable characteristics, which are influenced both by the genotype and the environment. Genotyping (mapping and analyzing the genome) can be carried out in small pieces with microarrays, including single nucleotide polymorphism (SNP) microarrays, traditional Sanger sequencing, and next-generation sequencing.[1] Whole-genome sequencing is the analysis of the entire genomic DNA sequence of an organism rather than small fragments contained in an SNP. Among technologies being developed for engineering genes are DNA synthesis, CRISPR, TALEN, and zinc finger nuclease.[2]

Epigenomics. This is the study of the epigenome, which is made up of all the chemical compounds and proteins that can attach to DNA. These chemicals (also called epigenetic modifications) can turn genes on or off, controlling the production of RNA and resultant proteins in particular cells without directly changing the DNA sequence.[3] Among mapping and analyzing technologies that tend to be used in epigenomics (but also in other omics) are ChIPseq (a method used to identify the binding sites of DNA-associated proteins across the genome), ATAC-seq (a technique used to assess the accessibility of genome-wide chromatin), and mass spectrometry.[4] CRISPR can be used to engineer the epigenome, too. The science in this field is exploratory.

Transcriptomics. The transcriptome is the complete set of RNA transcripts produced at a given time and is highly dynamic. RNA is a polymeric molecule that is an intermediary between encoding DNA and resultant proteins that performs cellular functions. It is essential in coding, decoding, regulating, and expressing genes. Technologies include RNA-Seq, which uses next-generation sequencing to show the presence and quantity of RNA in a sample, whole transcriptome shotgun sequencing, and RNA microarrays.[5] Engineering technologies include RNA editing and RNA silencing or siRNA.[6] The science in this field is exploratory.

Proteomics. This discipline relates to the proteome, the entire set of proteins in a cell or organism, with changes in quantity and composition over time. These proteins influence almost every aspect of biology, from cell structure to metabolism, transport, and signaling pathways. Debate surrounds what constitutes proteomics. We define proteomics as

1 Next-generation sequencing (NGS) is a catch-all term that refers to a range of modern high-throughput DNA sequencing technologies in which millions or billions of small DNA fragments can be sequenced in parallel. The sequences of these small fragments will be pieced together by mapping against the human reference genome.

2 Transcription activator-like effector nucleases (TALEN) are enzymes engineered to enable targeted modification of any DNA sequence in a large range of organisms. Zinc finger nuclease is a class of engineered proteins that bind DNA and create double strand breaks at user-specified locations to facilitate targeted editing of the genome.

3 When epigenomic compounds attach to DNA and modify DNA function, they are said to have "marked" the genome. Epigenetic modifications in some cases can be inherited through the generations. Environmental influences, such as a person's diet and exposure to pollutants, can also affect the epigenome.

4 Mass spectrometry is a tool used for measuring the mass-to-charge ratio of one or more molecules present in a sample. Mass spectrometers can be used to identify unknown compounds by determining their molecular weight, to quantify known compounds, and to determine the structure and chemical properties of molecules. They are used in epigenomics, proteomics, metabolomics, glycomics, and microbiomics.

5 Rohan Lowe et al., "Transcriptomics technologies," *PLoS Computational Biology*, May 2017, Volume 13, Issue 5.

6 Hassan Dana et al., "Molecular mechanisms and biological functions of siRNA," *International Journal of Biomedical Science*, June 2017, Volume 13, Number 2.

large-scale study of proteins rather than the study of a single protein. For this research, traditional methods of targeting and manipulating proteins using small molecules or biologics such as enzymes, antibodies, and hormones do not fall into our category of omics and molecular technologies. Mapping and analyzing technologies here include de novo protein synthesis and mass spectrometry.[7] They also include SOMAmer array (a proprietary platform of Somalogic), multiplex bead-based immunoassays (Luminex platform), ultrasensitive protein-binding array (Quanterix platform), and protein crystallization. This is an emerging area of research.

Metabolomics. This is the study of metabolites, which are the small-molecule intermediates and products of metabolism.[8] We classify this research as exploratory. Mapping and analysis tools included here are primarily mass spectrometry and nuclear magnetic resonance (NMR) spectroscopy.[9]

Glycomics. This nascent field relates to the structure and function of the complete set of glycosylated (glycosylation is the reaction in which a carbohydrate is attached to a hydroxyl or other functional group of another molecule) products such as glycans. Mapping and analysis technologies include mass spectrometry and high-performance liquid chromatography.[10]

Lipidomics. This is research into the complete range of lipids.[11] The technologies are the same as in metabolomics. This is a nascent field.

Microbiomics. This is the study of the microbiome, an area of increasing interest that we classify as emerging. The microbiome consists of all the microbes in a population such as the human gut or skin, and in the soil around farms. Humans are largely made up of microbes—indeed, they outnumber human cells.[12] Bacteria in the microbiome help us to digest food, regulate our immune systems, protect against other bacteria that cause disease, and produce vital vitamins.[13] Mapping and analysis technologies here are DNA sequencing and mass spectrometry. Engineering technologies include microbiome transplantation and genetically engineering specific microbes to alter a microbiome.

Single-cell omics. This is an area that applies to all omics. It is the study of individual cells in a way that captures the diversity, heterogeneity, and dynamics of single cells instead of the average signal from a set of heterogenous cells collected in a typical sample. For example, while performing DNA sequencing of individual cells in a tumor, it may be possible to assess the distribution of mutations within it; some cells will have all the mutations while others will have only some of those that led to malignancy.

Cell-free sequencing. It is possible to sequence fragments of DNA or RNA that are floating freely in the bloodstream rather than directly sampled from the source cells. In humans, this type of sampling is considered noninvasive compared with having to biopsy a tumor (termed "liquid biopsy") or the developing parts of a fetus, for example.[14]

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7 Mass spectrometry is well established and is widely used to analyze biological samples. As interest in our desire to understand the proteome increases, incremental improvements have been made. A recent development in mass spectrometry was the novel mass spectrometer (Orbitrap). See Xuemei Han, Aaron Aslanian, and John R. Yates, III, "Mass spectrometry for proteomics," *Current Opinion in Chemical Biology*, October 2008, Volume 12, Issue 5.

8 Metabolomics is the comprehensive identification and quantification of the complete set of metabolites (substrates, intermediates, and products of metabolism) of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time.

9 Nuclear magnetic resonance (NMR) spectroscopy is an analytical technique for determining molecular structures. Applications include determining the content and purity of a sample as well as its molecular structure, and metabolomics.

10 High-performance liquid chromatography is a form of column chromatography that separates, identifies, and quantifies components dissolved in a liquid solvent with a high analytical resolution.

11 This is the comprehensive identification and quantification of the complete set of lipids (the lipidome) of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time.

12 Ron Sender, Shai Fuchs, and Ron Milo, "Revised estimates for the number of human and bacteria cells in the body," *PLoS Biology*, August 2016, Volume 14, Issue 8.

13 *Fast facts about the human microbiome*, University of Washington Center for Ecogenetics and Environmental Health, January 2014; and M. Hasan Mohajeri et al., "The role of the microbiome for human health: From basic science to clinical applications," *European Journal of Nutrition*, May 2018, Volume 57, Supplement 1.

14 Cell-free DNA/RNA analysis, often abbreviated to cfDNA/cfRNA, is the sequencing of DNA or RNA outside a cell, in the bloodstream, for instance.

Exhibit 2

A range of scientific research streams are collectively known as omics.

Intracellular—flow of genetic information	**Epigenomics**		DNA modifications	Epigenetic marks that regulate gene expression (eg, DNA methylation, histone protein modification)
	Genomics		DNA	Full genetic complement of an organism (DNA); relatively static over time
	Transcriptomics		RNA	Complete set and quantity of RNA transcripts that are produced at a given time
	Proteomics		Protein	Entire set of proteins of an organism with changes over time
Intracellular—products of metabolism	**Metabolomics**		Metabolite	Set of metabolites, small-molecule intermediates, and products of metabolism
	Glycomics		Glycan	Structure and function of the complete set of glycosylated products (eg, glycans)
	Lipidomics		Lipid	Complete set of lipids produced
Other	**Microbiomics**		Microbe population	All microbes in a population (eg, the human gut)
	Single-cell omics		Human and other cells	Captures single-cell-level nuances that aggregation across multiple cells would miss
	Circulating cell-free DNA or RNA analysis		DNA/RNA in bloodstream, not in cell	Noninvasive genome or transcriptome information

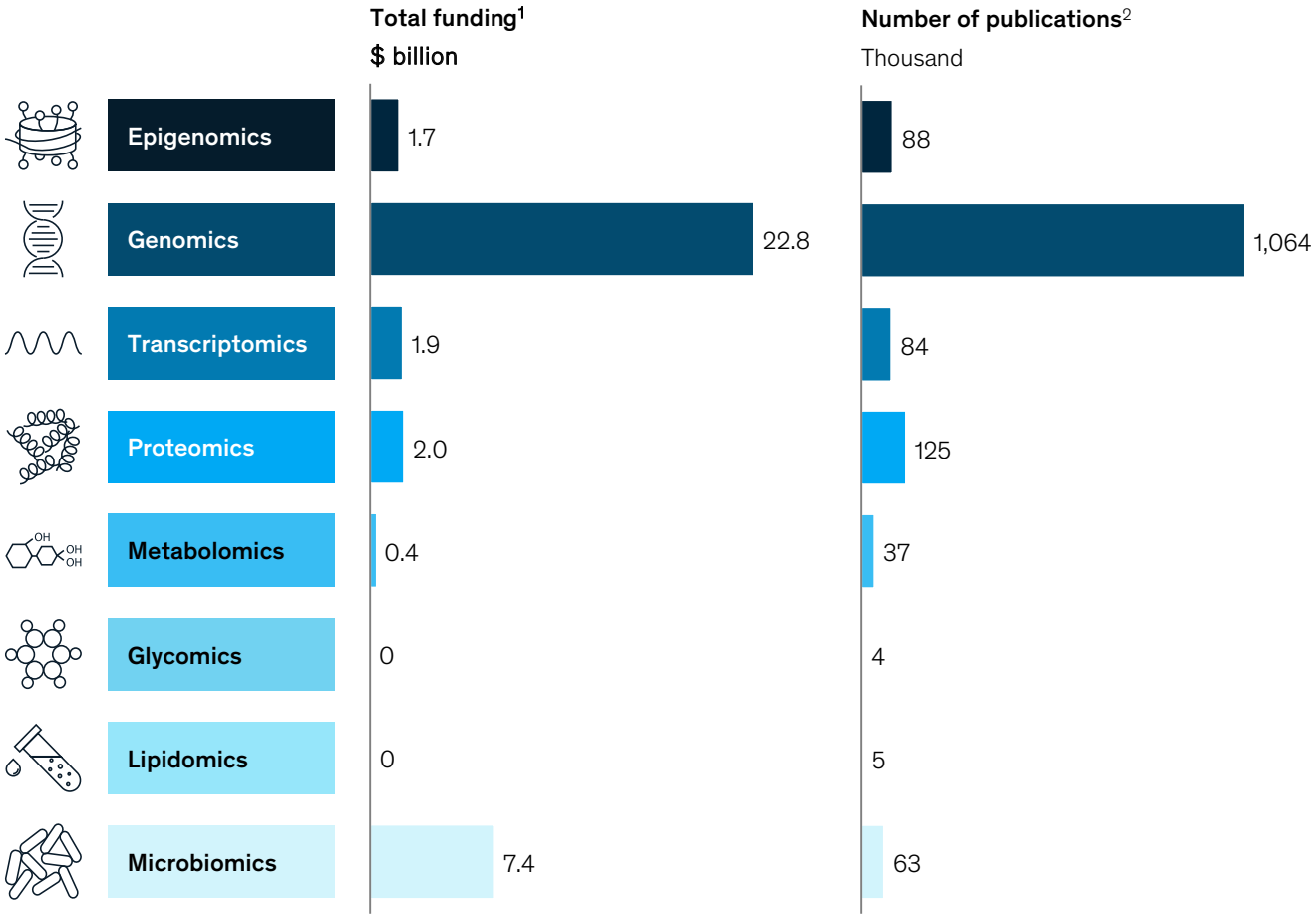
Regulation
Transcription
Translation

Source: McKinsey Global Institute analysis

Exhibit 3

Genomics is by far the most scientifically and commercially advanced of the omics.

2001–19



1. Based on PitchBook keyword search for startups that have a particular omics (or variation of keyword such as "epigenome") in their description; includes all venture capital stages (from accelerator/incubator to all series) and crowdfunding.
2. Based on PubMed keyword search for all publications containing a particular omics (or variation of keyword) in document.

Note: This is not an exhaustive list of omics. Other omics include immunomics (immune system genes/proteins, etc), fluxomics (rates of metabolic reactions), pharmacogenomics (response to drugs), viromics (viruses), metagenomics (genomes from environmental samples), and metaproteomics (proteins from environmental samples). Data as of March 2020.

Source: Crunchbase; PubMed; McKinsey Global Institute analysis

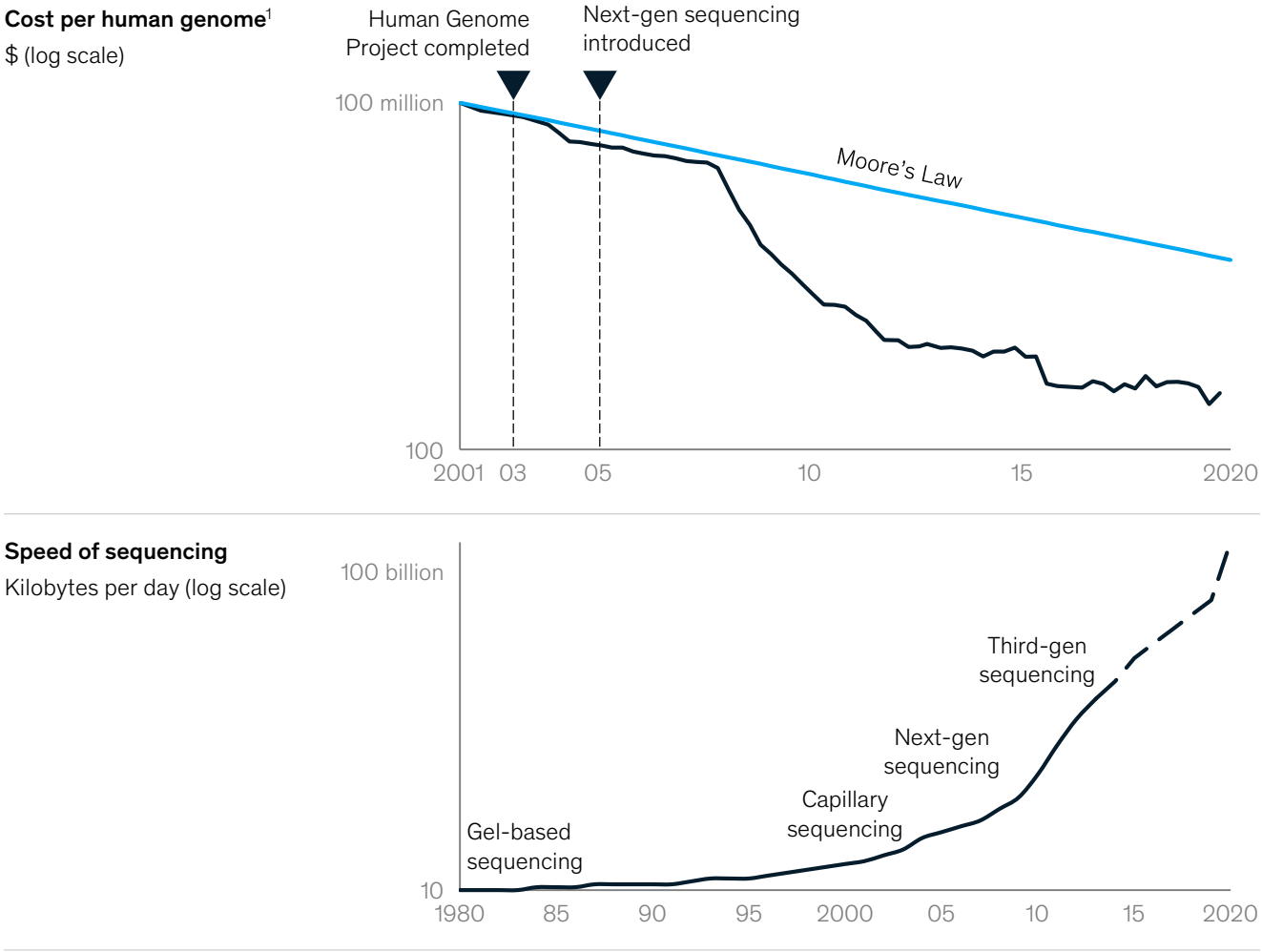
The cost of mapping, sequencing, and analyzing the genome has fallen even as the speed has increased in recent years (Exhibit 4). The cost of DNA sequencing is declining at a quicker pace than Moore's Law, which holds that the processing power of computers doubles roughly every 18 months for the same cost. The sequencing of the first human genome cost almost $3 billion. In 2019, the cost was less than $1,000.[59] Within a decade, the cost could be less than $100.[60] DNA testing is also increasingly sensitive, able to detect even fragments circulating in the blood. A fall in the cost of computing has enabled next-generation DNA sequencing, a range of modern techniques in which millions or billions of DNA strands can be sequenced in parallel, and then assembled into a single sequence. This assembly is needed because it is not possible to sequence a whole genome directly in one read using current sequencing technologies.[61] Current so-called "Third Generation Sequencing" is

[59] Joe Andrews, "23andME competitor Veritas Genetics slashes price of whole genome sequencing 40% to $600," CNBC, July 1, 2019.
[60] Kristen V. Brown, "A $100 genome is within reach, Illumina CEO asks if world is ready," Bloomberg, February 27, 2019.
[61] Alice Maria Giani et al., "Long walk to genomics: History and current approaches to genome sequencing and assembly," *Computational and Structural Biotechnology Journal*, 2020, Volume 18.

under development to enable sequencing an entire strand of DNA without breaking it into smaller strands.[62]

Exhibit 4

Rapid advances in computing, bioinformatics, and AI are enabling the analysis of omics data.



1. Data do not capture all costs associated with genome sequencing and include only production-related costs (labor, instruments, informatics, data submission).

Source: National Human Genome Research Institute; www.yourgenome.org; McKinsey Global Institute analysis

In the wake of the COVID-19 outbreak, scientists were able to sequence and publicly share the whole coronavirus genome just a few weeks after the first cases were reported in December 2019.[63] By comparison, during the SARS outbreak in 2002, full genome sequencing of the virus took more than five months after the first reported case.[64]

A similar dynamic interaction may take place between cheaper computing and the other omics as they develop. Advances in bioinformatics and AI mean that it is possible to mine much more information and insight from omic data sets. AI is enhancing these techniques. Bioinformatic techniques are needed to analyze and interpret data generated from omics, and

62 Third-generation sequencing is defined in various ways, but is generally taken to mean technologies that can sequence single DNA molecules without amplification and can produce much longer reads than next-generation sequencing.

63 WHO Timeline – COVID-19, www.who.int/news-room/detail/08-04-2020-who-timeline---COVID-19.

64 Paul A. Rota et al., "Characterization of a novel coronavirus associated with severe acute respiratory syndrome," *Science*, May 2003, Volume 300, Issue 5624.

AI promises to further enhance our understanding of all omic data sets and thereby enable a proliferation of applications. These complementary technologies have already enabled computer-intensive research such as genome-wide association studies (GWAS) that find associations between a particular human trait and variation in a genetic sequence throughout the genome across a large population.[65] GWAS are responsible for a wave of discoveries about the risk factors for common diseases. In a GWAS, researchers use computers to compare genomes across large populations, including some people who have a particular disease and many who don't. Subject groups that are otherwise well matched in aspects such as age and gender are sequenced to find areas of consistent differences, that is which genes are associated with which traits. If such areas are discovered, this helps scientists to zero in on parts of the genome that are responsible for the risk of disease.[66]

Genomic engineering technologies have shown exponential improvement. Technologies in DNA synthesis are developing. Although the ability to synthesize DNA de novo is limited in comparison with sequencing DNA, the gap is closing.[67] New inkjet- and semiconductor-based technologies have reduced costs and, at the same time, increased the accuracy of microarray-based DNA synthesis. Synthesized DNA strands can now be longer and cheaper than ever before. At the same time, DNA editing is advancing rapidly. It is now possible to edit genomic sequences—program life, if you will—more efficiently and effectively through tools such as CRISPR applied to human, plant, animal, and microbial DNA.[68] Research teams around the world developed the technology, which is within the capabilities of a basic biology lab to use.

CRISPR is relatively precise and cost-efficient because it requires only one endonuclease (an enzyme that breaks down a nucleotide chain into two or more shorter chains by cleaving the phosphodiester bond within a polynucleotide chain) and a short single strand of gRNA (guide RNA).[69] The first human clinical trials of CRISPR were held in 2016 by researchers at Sichuan University in China who injected a cancer patient with cells containing CRISPR-edited genes.[70] In 2016, 1,097 CRISPR patents were issued. By 2017, the number of CRISPR patents had risen to 1,303. It took only two years to develop the science for CRISPR and only one to commercialize this approach. Recent advances have made it possible to modify multiple target sites—about 25—within genes in a cell simultaneously.[71] These advances have also set off a new generation of bioengineering research in the field of synthetic biology, which has provided the basis for many of the technologies covered in the biomolecules area.

Mass spectrometry underlies a number of the nonnucleotide (DNA, RNA) omics, but thus far advances have not been as rapid. Scientists face a number of challenges. More sensitivity is needed. Today, proteins, metabolites, and lipids cannot be amplified for detection like DNA or RNA, meaning that differences are much harder to detect. There is too much complexity because of the heterogeneity of proteins as well as the greater number of amino acids that make up proteins (20) compared to the nucleotides that make up nucleic acids (four). This makes proteomics inherently more difficult than nucleotide-based omics.[72] The degree of automation is limited, and skilled technicians still have to do a considerable amount of manual

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65 Genome-wide association studies find associations between a particular human trait and variation in genetic sequence throughout the genome across a large population. In these studies, people who have a particular disease and many who don't are sequenced in order to find areas of consistent differences. If such areas are discovered, this helps scientists to zero in on parts of the genome that are responsible for the risk of disease.

66 *What are genome wide association studies (GWAS)?*, Train Online, European Molecular Biology Laboratory European Bioinformatics Institute; and genome-wide association studies (GWAS), US National Human Genome Research Institute.

67 De novo synthesis is the synthesis of complex molecules such as DNA and protein from simple molecules such as sugars or amino acids, as opposed to recycling after partial degradation.

68 Liting You et al., "Advancements and obstacles of CRISPR–Cas9 technology in translational research," *Molecular Therapy, Methods & Clinical Developments*, June 2019, Volume 13.

69 Guide RNAs or gRNAs are RNA sequences that guide Cas nuclease to a target region of DNA.

70 The same team went on to inject patients with non-small-cell lung cancer with T-cells removed from patients' blood and modified using CRISPR. See David Cyranoski, "CRISPR gene-editing tested in a person for the first time," *Nature*, November 15, 2016.

71 Carlo C. Campa et al., "Multiplexed genome engineering by Cas12a and CRISPR arrays encoded on single transcripts, " *Nature*, August 12, 2019.

72 Simone Sidoli, Katarzyna Kulej, and Benjamin A. Garcia, "Why proteomics is not the new genomics and the future of mass spectrometry in cell biology," *Journal of Cell Biology*, January 2017, Volume 216, Issue 1.

work in preparing samples. Scalability is limited because, for instance, high-throughput proteomic analyses such as flow cytometry and ELISA still require antibodies.[73] Overall, high-throughput mass spectrometry is still not cost-effective. Furthermore, the Human Proteome Project, launched in 2010, lacks deeply annotated reference maps like those developed as part of the Human Genome Project.[74] Incomplete and sometimes inaccurate databases hinder proteomic annotation, and procedures for preparation and analysis of samples vary among labs and research groups. Finally, mass spectrometry tends to rest on proprietary software rather than the open-source software typical of genomic bioinformatics, which also slows the rate of progress.[75]

In many cases, engineering the transcriptome, proteome, epigenome, glycome, and lipidome is accomplished through modified genetic sequences that express modified RNA and proteins to effect changes in the cell. However, some molecular technologies directly involve the administration or modification of RNA or proteins, some of which are synthesized de novo.

Biosystems

Biosystems relates to the mapping and engineering of cells, tissues, and organs, and includes stem cell technologies, uses for transplantation, as well as the 3-D printing of tissues. The science of mapping and characterizing biosystems has advanced significantly. Since 2016, the Human Cell Atlas project has created the most comprehensive reference maps of all human cells in a healthy body with unprecedented detail, cell types and subtypes, numbers, locations, cell states, cell lineage, and molecular components. Once complete, it will be a fundamental resource for scientists, allowing them to better understand how healthy cells work as a basis for research, diagnosis, monitoring, and treatment. The maps are expected to help identify markers and signatures for different diseases and uncover new targets for therapeutic intervention. In addition to mapping, enormous progress also has been made on the engineering front. Regenerative medicine is a promising field that could lead to treatments that do not exist today for patients with spinal cord injuries or in need of organ transplants.[76] Progress in biosystems arises out of advances in omics and molecular technologies such as genetic engineering, although the engineering of tissues can also be undertaken without such technology. Other examples of biosystems exist in food (meat grown in labs) and materials (one company is making leather using mushroom cells).

In the medical field, one of the key components of biosystems is the evolution of stem cell research. It is hard to pinpoint exactly when, and by whom, what we now call stem cells were first identified, although the consensus is that the first to define the key characteristics of these cells rigorously was a team in Toronto in the 1960s.[77] Since then, the science and its application have progressed significantly. In 1998, a method to derive and maintain stem cells with the ability of differentiating into cells of all tissues in the body from human embryos was reported, intensifying the interests of using stem cells' properties in regenerative medicine. Later in 2006, scientists learned how to reprogram adult cells into cells known as induced

[73] Flow cytometry is a laser-based technology that counts, sorts, and profiles cells or particles within a liquid suspension. ELISA is short for enzyme-linked immunosorbent assay—it detects and measure the amount of a substance in a solution such as serum. This technique utilizes antibodies linked to enzymes that can produce a color change or other measurable effect.

[74] P. Legrain et al., "The human proteome project: Current state and future direction," *Molecular & Cellular Proteomics*, July 2011, Volume 10, Issue 7; C. Manzoni et al., "Genome, transcriptome and proteome: The rise of omics data and their integration in biomedical sciences," *Brief Bioinform*, March 1, 2018, Volume 19, Number 2; and S. C. Nanita and L. G. Kaldon, "Emerging flow injection mass spectrometry methods for high-throughput quantitative analysis," *Analytical and Bioanalytical Chemistry*, December 15, 2015, Volume 408, Number 1.

[75] Simone Sidoli, Katarzyna Kulej, and Benjamin A. Garcia, "Why proteomics is not the new genomics and the future of mass spectrometry in cell biology," *Journal of Cell Biology*, January 2017, Volume 216, Issue 1.

[76] Regenerative medicine is the process of replacing, engineering, or regenerating human or animal cells, tissues, or organs to restore or establish natural function.

[77] A. J. Becker, E. A, McCulloch, and J. E. Till, "Cytological demonstration of the clonal nature of spleen colonies derived from transplanted mouse marrow cells," *Nature*, February 1963, Volume 197, Number 4866; and Mighel Ramalho-Santos and Holger Willenbring, "On the origin of the term 'stem cell,'" *Cell Stem Cell*, June 7, 2007, Volume 1, Issue 1.

pluripotent stem cells or iPSCs.[78] The discovery of iPSCs was important because it uncovered new knowledge about how differentiation works and provided an alternative to embryonic stem cells, whose use had raised ethical issues.[79] iPSCs take adult cells and apply different molecular factors that change the cells back to undifferentiated or "blank" cells that can then be induced to develop into other types of cells, such as spinal cord or liver cells. Adult stem cells are usually used to repair and replace cells, for instance in bone marrow.

Research continues into how cells differentiate. Scientists have already demonstrated, for example, that stem cells can be differentiated into cone cells, one of the two types of photoreceptor cells in the retina that are responsible for color vision and light sensitivity; there is the potential, therefore, to treat blindness caused by macular degeneration.[80] It is now thought that mesenchymal stem cells found in bone marrow may be able to differentiate into many other cell types, but no treatments using these cells have yet been clinically proven.[81] Interest in this area is intense. In 2016, there were more than 490 clinical trials using mesenchymal stem cells.[82]

The ability to build biosystems from a single cell into tissues and even complete organs has gradually grown closer as the cost of 3-D bioprinting falls and microfabrication technology advances. The cost of both bioprinters and biomaterials is declining as demand rises and novel materials are developed and become available.[83] Commercial 3-D bioprinters cost $5,000 to $200,000, but research labs are repurposing low-cost 3-D printers such as MakerBots to bring the price down to about $500.[84] Often the creation of complex tissues and organs requires more than simply printing the right cells in the right shapes. Researchers have used advances in microfluidics and biomaterials to create the scaffolds and complex arrangements needed to mimic tissue microenvironments, moving closer to creating fully functioning organs.[85] Further scientific advances will be needed to make the printing of fully functioning organs a reality.[86] Pioneering scientist Jennifer Lewis at Harvard, who is working on printing organs, says that this is decades away.[87]

Biomachine interfaces

Biology and machines can now interact, creating biomachine interfaces. The technology now exists to measure neural signals in real time and translate them into actions for a computer or machine; it is also possible to use machines directly to influence and modify neural systems (Exhibit 5).[88]

Innovation in software and hardware has enabled this area. It is now possible to acquire signals of neural measurements with improved temporal and spatial resolution. Sensors can be placed on the scalp, on the exposed surface of the brain, or directly into the cortex to measure single neuronal activity. It is increasingly possible to extract features using improved

78 These are adult cells (for instance, skin cells) that are reprogrammed into an embryonic stem cell-like state that enables the development unlimited amounts of any type of human cells. In this process, adult cells (for instance, skin or blood cells) are reprogrammed back into an embryonic-like pluripotent state that enables the development of an unlimited source of any type of human cell needed for therapeutic purposes. See *History of stem cell use*, University of Nebraska Medical Center.

79 Embryonic stem cells are stem cells that comprise human embryos that are three to five days old. They are pluripotent stem cells, meaning they can give rise to many cell populations in the body.

80 Valeria Chichagova et al., "Cellular regeneration strategies for macular degeneration: Past, present, and future," *Eye*, May 2018, Volume 32, Issue 5.

81 *What diseases and conditions can be treated with stem cells?*, Euro Stem Cell.

82 Mesenchymal stem cells are stem cells that are found in various tissues (such as bone marrow) that can differentiate into a variety of cell types, such as bone, cartilage, muscle, and fat. See *Stem cell research progress in the US: Where are we now?*, In Vivo, November 2018.

83 Andrew J. Capel et al., "3-D printing for chemical, pharmaceutical and biological applications," *Nature Reviews Chemistry*, November 2018.

84 Adam Feinberg, "Carnegie Mellon designs low-cost, high-efficiency 3-D bioprinter," *Robotics Tomorrow*, May 29, 2018.

85 Manuela E. Gomes et al., "Tissue engineering and regenerative medicine: New trends and directions—a year in review," *Tissue Engineering Part B, Reviews*, Volume 23, Number 3, June 2017.

86 David Grossman, "Scientists successfully 3-D print an organ that mimics lungs," *Popular Mechanics*, May 3, 2019.

87 Sean O'Neill, "How to 3D-print a living, beating heart," *New Scientist*, November 14, 2018.

88 For more, see, for example, Sarah N. Abdulkader, Ayman Atia, and Mostafa-Sami M. Mostafa, "Brain computer interfacing: Applications and challenges," *Egyptian Informatics Journal*, July 2015, Volume 16, Issue 2; and Eduardo López-Larraz et al., "Brain-machine interfaces for rehabilitation in stroke: A review," *NeuroRehabilitation*, Volume 43, Issue 1, 2018.

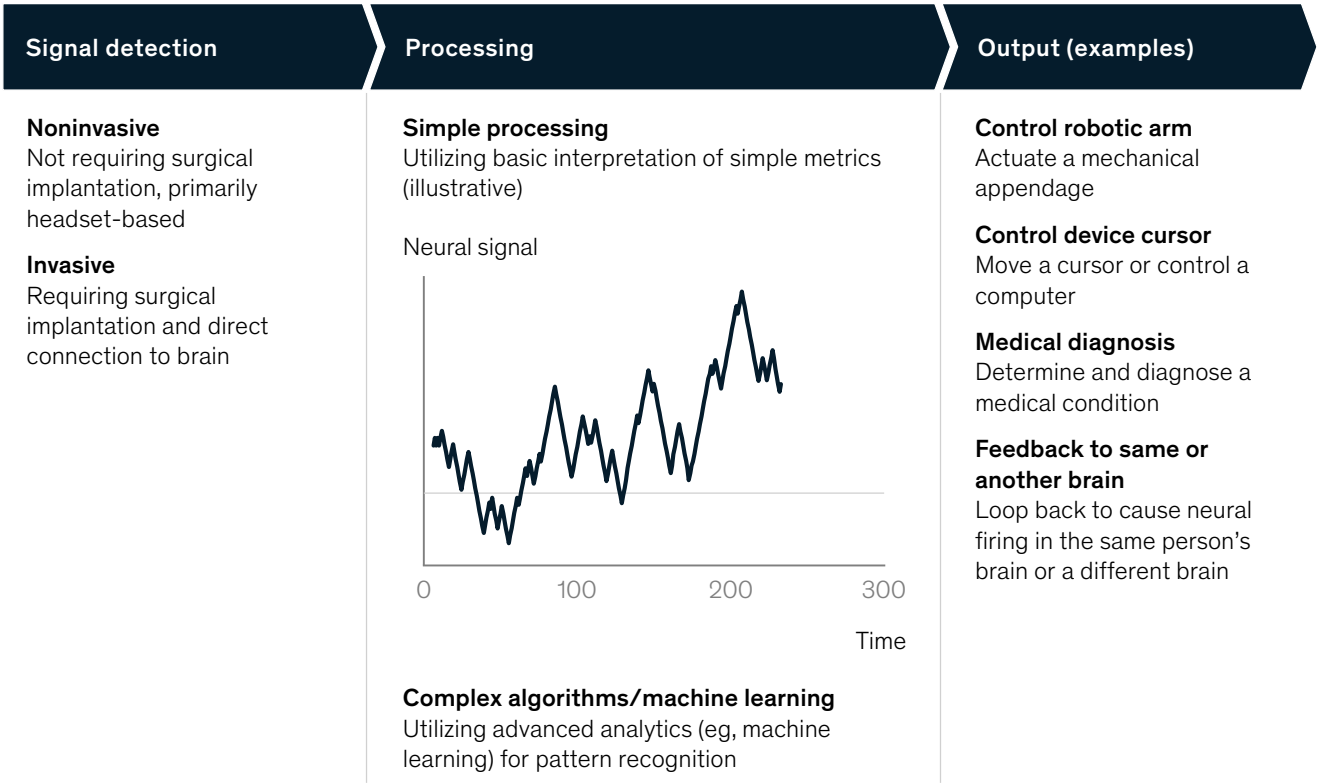
processing algorithms to find meaningful content even within a noisy signal. Improved machine learning enables biomachine interfaces to classify features and accurately map them into interpreted categories. Classifications can then be translated to control software via a mouse or keyboard and hardware such as prosthetics.

Biomachine interfaces include a range of technologies, from simple, noninvasive biofeedback devices that are already available to consumers—and could be refined and popularized in the immediate future—to speculative concepts whose commercialization and adoption remain a long way off. The latter category includes direct brain-to-brain communication and education through neural inputs.

There are still issues to resolve. For instance, noninvasive techniques still lack the neuron-scale resolution needed for many applications. Implanted devices are needed for high-resolution reading, but this level of invasiveness is impeding progress. Any technology currently capable of registering neural brain activity at a resolution of less than hundreds of neurons requires implanting devices in the skull.[89] This not only raises ethical questions about using humans to test and develop this new technology, but also presents severe risks of infection or complications arising from such a profound surgical procedure.[90]

Exhibit 5

The key stages of a biomachine interface are signal detection, processing, and output.



Source: McKinsey Global Institute analysis

[89] Mikhail A. Lebedev and Miguel A. Nicolelis, "Brain-machine interfaces: From basic science to neuroprostheses and neurorehabilitation," *Physiological Reviews*, Volume 97, Issue 2, April 2017.
[90] Ibid.

Biocomputing

Biocomputing includes the use of cells or molecules such as DNA or enzymes to solve mathematical problems, a process known as biology-based parallel computing. This area is in a relatively early phase of development but has potentially exciting applications. Theoretically, biology-based parallel computing can perform many calculations in parallel, with each molecule or cell performing one computation.[91] For now, however, researchers have not progressed beyond solving theoretical problems that traditional computers can easily handle.[92] A key limitation is that while computations with biological substrates can quickly be parallelized by growing more cells or using a large quantity of molecules, substantial up-front effort is required to engineer cells or systems to solve each problem. Therefore, there is a trade-off between any theoretical advantages in computation time and the months of effort it would take to build a biologic substrate-based computer.

In contrast to computation, biological data storage—using DNA as a data-storage medium—has immediate potential to outpace electronic means of storage. Extremely stable and information-dense, DNA can store 5.5 petabits of encoded data in one cubic millimeter, with each bit duplicated 100 times for redundancy. Looking at this from another perspective, it has been estimated that one kilogram of DNA could hypothetically store all current data in the world.[93] DNA is very stable, even in suboptimal conditions; it can be readable after thousands of years.[94] DNA could eventually replace magnetic tape for long-term archival storage and arguably is the only current biocomputing technology that could rival traditional alternatives.

Several trends in science and technology are powering human understanding of biological processes and enabling us to engineer them for myriad uses. These technologies range from lower-cost, more rapid gene sequencing, to the ability to program genetic sequences as if they were computer code, to breakthroughs in neural sensing and signaling. In the following chapter, we look at the potential practical applications of these scientific breakthroughs as they move out of the lab and into commercial use.

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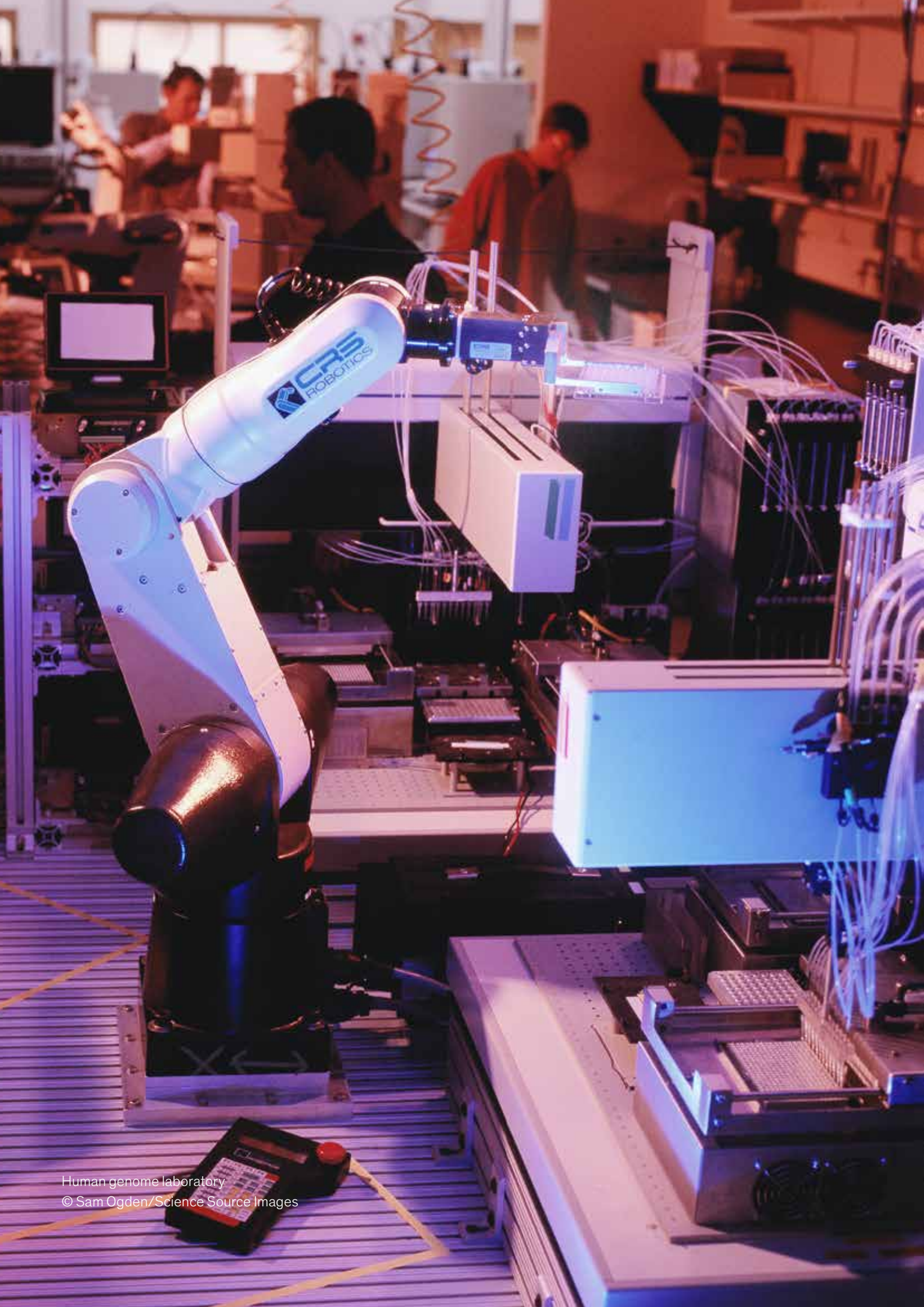
91 L. M. Adleman, "Molecular computation of solutions to combinatorial problems," *Science*, November 1994, Volume 266, Issue 5187.

92 Shaji Varghese et al., "Molecular computing: Paths to chemical Turing machines," *Chemical Science*, 2015, Volume 6, Issue 11; and Yaakov Benenson, "Biomolecular computing systems: Principles, progress and potential," *Nature Reviews Genetics*, July 2012, Volume 13, Number 7.

93 George I. Seffers, "Scientists race toward DNA-based data storage," *Signal*, September 1, 2019.

94 George M. Church, Yuan Gao, and Sriram Kosuri, "Next-generation digital information storage in DNA," *Science*, September 2012, Volume 337, Issue 6102.



Human genome laboratory
© Sam Ogden/Science Source Images

2. New capabilities could transform economies and societies

Scientific breakthroughs over the past two decades have laid the foundation for fundamentally new capabilities that have the potential to transform business, society, and the environment. They are the tools driving change. The effects will be felt across value chains, from how R&D is conducted to the physical inputs in manufacturing to the way medicines and consumer products are delivered and consumed. Two data points from our research give an idea of the potential scale and scope.

First, we estimate that as much as 60 percent of the physical inputs to the global economy could be produced biologically. Our analysis suggests that around one-third of these inputs are biological materials, such as wood, cotton, and animals bred for food. For these materials, innovations can, in principle, improve upon existing production processes. For instance, squalene, a moisturizer used in skin-care products, is traditionally derived from shark liver oil and can now be produced more sustainably through fermentation of genetically engineered yeast. The remaining two-thirds are not biological materials—examples include plastics and aviation fuels. These could, in principle, be produced using innovative biological processes or could be replaced with substitutes using bio innovations. For example, nylon is already being made using genetically engineered microorganisms instead of petrochemicals. To be clear, the full potential is a long way off, but even modest progress toward it could transform supply and demand and economics of, and participants in, the provision of physical inputs. Biology has the potential in the future to determine what we eat, what we wear, the products we put on our skin, and the way we build our physical world.

Second, as we discuss in more detail in later chapters, biological sciences could play a major role in reducing the current global disease burden. Still, the timing and adoption of these capabilities will vary. In this chapter, we identify some of the most important capabilities.

New capabilities are being created that provide the building blocks of profound change in economies and societies

In this section, we highlight five areas where the new capabilities could be deployed and, where measurable, the scale of their potential impact.

Biological means could be used to produce a large share of the global economy's physical materials, potentially with improved performance and sustainability

Materials have played such a fundamental role in human history that historians have named entire time periods after them—the Stone, Bronze, and Iron ages. Each step forward in the evolution of materials has heralded a paradigm shift in technology, society, and quality of life.

Now is the era of biology, which is increasingly being used to create novel materials that can raise quality, introduce entirely new capabilities, and offer more environmentally sustainable profiles.

Fermentation, for centuries used to make bread and brew beer, is now being used to create fabrics such as artificial spider silk. Leather is being made from mushroom roots instead

of animal hide.[95] US startup Tandem Repeat produces self-repairing, biodegradable, and recyclable fabric by isolating genes from squid that have the ability to synthesize self-healing fibers, and then producing fabrics through fermentation.[96] The fabric also minimizes microfiber shedding during washing, thereby reducing the flow of microplastics into the oceans. Meanwhile, biotech company Zymergen is creating renewable biomaterials for optical films used in displays, flexible electronics circuits, and hard, scratch-proof coatings.[97]

Cultured meat and seafood are not yet available for consumers to buy, but they could become cost competitive with meat from rearing animals in the next ten years, potentially taking pressure off land use, helping to slow deforestation, and lowering the burden on oceans. Reducing the cost of cultured meat to a competitive level will be challenging, but some companies, including Finless Foods, Mosa Meat, Memphis Meats, and Meatables are now experimenting with using synthetic molecules and stem cells to replace expensive growth factors.[98] Amyris produces a moisturizing oil, squalene, that is used in many skin-care products through fermentation of sugarcane via genetically engineered yeast, rather than by processing deep-sea-shark liver oil, which is costly and environmentally questionable. Not only can the company produce cost-effectively on a large scale, but it can also do so from a renewable source.[99]

A significant share of materials developed through biological means are biodegradable and generate less carbon during manufacture and processing than traditional materials. New bioroutes are being developed to produce chemicals such as fertilizers and pesticides. Work has already been done on new pesticides that uses gene silencing—RNA interference (RNAi)—that inhibits the life functions of insects; the first RNAi insecticide was approved for commercial use in 2017.[100] Some companies are using genetically engineered microbes to create biofuels for the aviation and marine industries.[101] One startup is using microorganisms to create an alternative to traditional cement that produces far less carbon emissions during its manufacture.[102]

Increased control and precision in methodology is occurring across the value chain, from delivery to development and consumption with more personalization

Advances in molecular biology have made R&D and delivery processes more precise and predictable. In healthcare, many medical treatments have been designed for the average patient, a one-size-fits-all approach that inherently means varying levels of efficacy. Using mounting knowledge of a person's genetic makeup and improved understanding of the link between genes and certain diseases, researchers now have significant scope to tailor medical approaches to the individual's genome—personalized or precision medicine.[103] Ever-cheaper genome sequencing means that such personalization is increasingly observed in medical practice, particularly in the diagnosis and treatment of rare disorders.[104] Advances in precision medicine have already led to powerful new discoveries and several new treatments tailored to a person's genetic makeup or the genetic profile of an individual's tumor. Patients with breast, lung, and colorectal cancers, as well as melanomas and leukemias, now routinely

95 Thomas Crow, "Mushroom leather: The key to sustainable fashion?," *Particle*, April 2019; and Eillie Anzilotti, "This very realistic fake leather is made from mushrooms, not cows," Fast Company, April 2018.

96 Tandem Repeat; and Simone Preuss, *Sustainable textile innovations, self-healing fibres made out of squid genes*, Fashion United, September 4, 2018.

97 "Sumitomo Chemical and Zymergen announce partnership to develop renewable specialty materials," Business Wire, April 17, 2019.

98 Matt Reynolds, "The clean meat industry is racing to ditch its reliance on foetal blood," *Wired*, March 20, 2018.

99 *Clean beauty, Biossance*, Amyris.

100 Brenda Oppert and Lindsey Perkin, "RNAiSeq: How to see the big picture," *Frontiers in Microbiology*, November 14, 2019; and Aggie Mika, "First RNAi insecticide approved," *The Scientist*, June 27, 2017.

101 Peggy Hollinger, "Greener biofuels battle for take-off to cut aviation emissions," *Financial Times*, March 30, 2020; Jonathan Saul, *Shipping companies, retailers look to develop cleaner marine biofuel*, Nasdaq, October 29, 2019; and Mike Kass et al., *Understanding the opportunities of biofuels for marine shipping*, Oak Ridge National Laboratory, December 2018.

102 Scott Patterson, "Growing bricks and more ways to shrink concrete's carbon footprint," *Wall Street Journal*, February 12, 2020.

103 For a fuller description, see, for example, *The Precision Medicine Initiative*, US Executive Office of the President, January 2015, obamawhitehouse.archives.gov/precision-medicine.

104 Andrew R. Scott, "Technology: Read the instructions," *Nature*, September 7, 2016.

undergo molecular testing to optimize treatments. Personalized medicine is not yet routine for most people, but it is spreading. This will benefit healthcare outcomes.

Precision also applies to agriculture, where increasingly the insights from a plant's or soil's microbiome can be used to optimize yields by enabling more targeted or economical agricultural production.[105] Personalization and precision are being applied to consumer goods and services such as individual nutrition plans based on genetic tests.[106]

The capability to engineer and reprogram human and nonhuman organisms is increasing

Healthcare is a big-ticket item across the world. According to the World Health Organization (WHO), global spending on health in 2017 was $7.8 trillion, or about 10 percent of global GDP. Between 2000 and 2017, global health spending increased by nearly 4 percent a year in real terms against annual GDP growth of 3.0 percent.[107] Of course, the cost of poor health goes far beyond the money spent on it by health systems—for instance, it compromises productivity and ultimately economic growth. Improving the health of populations is therefore a major economic issue as well as a human one. Biological sciences are already helping meet this challenge. Diagnosis of common disorders has been much faster and more accurate over the past ten years thanks to advances in large-scale parallel DNA sequencing.[108] Gene drives could be used to prevent vector-borne diseases, including malaria, dengue fever, schistosomiasis, and Lyme disease. Gene therapies could offer complete cures of some diseases for the first time through the direct editing of abnormal genes in cells in individuals. Gene therapies have been approved for beta thalassemia, spinal muscular atrophy, hemophilia, and some immune deficiencies, and trials were being conducted in 2019 for other monogenic diseases such as sickle cell anemia.[109] Such innovations could reduce healthcare spending and, by prolonging life spans and promoting health, boost productivity and growth if people are able to work longer if they so choose.

The same technical advances that are driving the capability to improve human health can be used to introduce valuable new traits that, for instance, improve the output or yield of nonhuman organisms like microbes, plants, and animals. Crops can be genetically engineered to taste better, produce higher yields, and be more heat- or drought-resistant, for instance—traits that could become even more important if climate change continues to increase global temperatures.[110] Microbes can be genetically engineered to produce different substances, from cellular vaccines to industrial enzymes. In the future, pets could be engineered to shed less hair, which may be popular with consumers. For nonhuman genetic engineering, the same ethical red flags apply as with humans.

New methodologies using automation, machine learning, and proliferating biological data are enhancing discovery, throughput, and productivity in R&D

In the past, scientists relied on finding random mutations to identify beneficial traits—discovery by accident. Today, increasingly there is a rational approach to R&D based on far greater information. And there is emerging evidence that the interaction between biology and computing can accelerate the R&D process, which could help address R&D's productivity problem. McKinsey analysis in 2017 found that the ratio of revenue to R&D spending in the biopharmaceutical industry hit a productivity nadir between 2008 and 2011.[111] The average

[105] Chrysi Sergaki et al., "Challenges and approaches in microbiome research: From fundamental to applied," *Frontiers in Plant Science*, August 2018, Volume 9.

[106] Aleksandra A. Kolodziejczyk, Danping Zheng, and Eran Elinav, "Diet-microbiota interactions and personalized nutrition," *Nature Reviews Microbiology*, December 2019, Volume 17, Issue 12; Monica Reinagel, "Personalized nutrition: The latest on DNA-based diets," *Scientific American*, September 27, 2019; and Anna Vesnina et al., "Genes and eating preferences, their roles in personalized nutrition," *Genes*, April 2020, Volume 11, Issue 4.

[107] *Global spending on health: A world in transition*, World Health Organization, 2019.

[108] H. Stranneheim and A. Wedell, "Exome and genome sequencing: A revolution for the discovery and diagnosis of monogenic disorders," *Journal of Internal Medicine*, August 2015, Volume 279, Issue 1.

[109] Alex Philippidis, "25 up-and-coming gene therapies of 2019," *Genetic Engineering & Biotechnology News*, May 20, 2019.

[110] *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020; and Claudia Parisi, Pascal Tillie, and Emilio Rodríguez-Cerezo, "The global pipeline of GM crops out to 2020," *Nature Biotechnology*, January 2016, Volume 34, Issue 1.

[111] Sastry Chilukuri, Edd Fleming, and Ann Westra, *Digital in R&D: The $100 billion opportunity*, McKinsey & Company, December 2017.

cost of bringing a drug to market has been estimated at $2.6 billion, or 140 percent higher than a decade ago.[112] Genomics could be deployed to reduce the development costs of a new drug by nearly 50 percent.[113] Biotech companies and research institutes are increasingly using robotic automation and sensors in labs to accelerate speed and accuracy compared with traditional labs that tend to rely on human scientists conducting experiments manually.[114] Research from one biotech company concludes that throughput can increase up to ten times compared with traditional corporate or academic labs, significantly increasing the probability of scientific breakthroughs, significantly accelerating cycle times, and potentially reducing costs.[115] Advanced analytics using machine learning can lead to better insights during the R&D process, and more systematic links between health data and diseases can help scientists and health practitioners to arrive more quickly at optimal treatments.

Potential is growing for interfaces between biological systems and computers

Humankind increasingly works in tandem with machines—our workplaces are more automated, and we are ever more reliant on our smartphones. But a more intimate relationship is developing, enabled by sophisticated algorithms and systems, in which machines are able to use signals from the brain and even send signals back, advancing or restoring human capabilities. One prominent type of biomachine interface is the neuroprosthetic that restores lost sensory functions by delivering stimulation to the brain based on light or sound; other neuroprosthetics are able to record and interpret signals from the brain to control physical movement of a prosthetic limb with increasing exactitude. There have been large strides in bionic vision over the past two decades. Approved in the EU and the United States, SecondSight's retinal implant has enabled clinically blind patients to distinguish shapes, sense light, and even read print.[116] Much progress is being made in treatments and diagnostic technology that stimulate the brain or interpret its signals. Deep brain stimulation (DBS), a procedure in which a stimulator in the patient's chest is connected via electrodes to parts of the brain, was approved for the treatment of epilepsy and Parkinson's disease some years ago. Now research is under way into whether DBS could help patients suffering from Alzheimer's disease, depression, and anxiety.[117]

Just as digital technologies are able to enhance biological systems, in the case of biomachine interfaces, the relationship can also work the other way around: biology may be a solution to some established challenges of the digital world. Consider, for instance, the headache of storing data. Every day, an estimated 2.5 quintillion bytes of data is generated globally.[118] The world could run out of silicon to store data by 2040.[119] But biology offers a solution in DNA data storage. DNA is about one million times denser than hard-disk storage; one kilogram of DNA could hypothetically store all current data in the world.[120] DNA doesn't deteriorate and could therefore store data for hundreds or even thousands of years. Work is already under way exploring this area.

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112 Joseph A. DeMasi, Henry G. Grabowski, and Ronald W. Hansen, "Innovation in the pharmaceutical industry: New estimates of R&D costs," *Journal of Health Economics*, May 2016, Volume 47; and *The pursuit of excellence in new-drug development*, McKinsey & Company, November 2019.

113 Jakob Aptekar, Nicholas Donoghoe, Edd Fleming, Meredith Reichart, Erika Stanzl, and Kevin Webster, *Precision medicine: Opening the aperture*, McKinsey & Company, February 2019; and Steven M. Paul et al., "How to improve R&D productivity: The pharmaceutical industry's grand challenge," *Nature*, February 2010, Volume 9.

114 *Zymergen case studies*, Partnership on AI.

115 *Zymergen case studies*, Partnership on AI; Melanie de Almeida, *Taking biotech to the next level with laboratory automation*, Labiotech, November 14, 2018.

116 Duncan Graham-Rowe, "Visions of the future," *Wired*, August 6, 2010.

117 Majed Aldehri et al., "Deep brain stimulation for Alzheimer's disease: An update," *Surgical Neurology International*, March 2018; Catherine Offord, "Deep brain stimulation improves depression symptoms: Study," *The Scientist*, October 7, 2019; and *Deep brain stimulation for anxiety disorders in adults*, NYU Langone Health.

118 Bernard Marr, "How much data do we create every day? The mind-blowing stats everyone should read," *Forbes*, May 21, 2018.

119 Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016.

120 Ibid.

The potential impact of these capabilities on economies and societies could be broad in both scope and scale

These emerging capabilities could touch multiple domains in the economy, both directly and indirectly. Applications may change everything from the food we consume to textiles to the types of health treatments we receive and how we build our physical world. The potential value is substantial. For instance, at least 45 percent of the global disease burden could be addressed from what is scientifically conceivable today. Bio innovations could transform the way we prevent, diagnose, and treat diseases.

These innovations will also transform research and development—and indeed have already begun to do so, through high-throughput screening, CRISPR, and machine learning that leverages biological data. We estimate that roughly 30 percent of private-sector R&D in major economies is in industries where biological data, biological inputs, or biological means of production could be used.[121] The power of these biological technologies, their effects on production and markets, and broader societal influence suggest that the advances in biology could even rival other periods of scientific and technological ferment, such as the Industrial Revolution and the mass adoption of digital technologies in recent years, as discussed in the next section.

Some of the potential applications we identify are still at an early stage, and many others may surface in coming years. The full impact of the value of biological applications remains in the future, but already, it is possible to identify some key applications and domains where these technologies could be deployed. Over the past five to ten years, proof-of-concept experimentation has increasingly emerged from the lab and into the marketplace. Many applications, particularly in health and agriculture, are now in the commercialization phase. Products from materials to chemicals are being replaced by alternatives produced and processed using biological means that are often more efficient and, in many cases, put less pressure on the environment. While the early direct impacts of biological technologies are for now primarily concentrated in certain domains, such as human health and agriculture, they could spread downstream to other sectors and to society more broadly.

Biological advances create new capabilities that, in combination, could lead to sweeping change in economies and societies. The changes they will likely bring could be broad-based in many respects, and there is one aspect in which biological sciences are unique: the significant risks they entail. We turn to a discussion of risks in the next chapter.

[121] R&D funded by business enterprise sector across major regions such as China, the EU, and the United States. Analysis is based on data from EU Industrial R&D Investment Scoreboard, 2019.

Man wearing protective suit working with dangerous viruses in a laboratory
© D-Keine/E+/Getty Images

3. Profound and unique risks and issues

Biology is rich with possibility and opportunity, but also fraught with risks. It will preserve life through innovative treatments tailored to our genomes and microbiomes. But biology could also be the greatest threat to life if it is used to create bioweapons or viruses that forever poison ecosystems. It may even be that some of the unique risks associated with biology could outweigh the potential benefits of some applications.

Issues of data privacy and consent that are already being fiercely debated in the case of digital technologies and AI are even more pressing in biology, where the data being gathered come from our bodies and minds, and couldn't be more personal and sensitive. And there is another paradigm shift from digital. We can unplug a computer, but biology, once unleashed, may not easily be switched off. Biological organisms are, by their nature, self-sustaining and self-replicating. Genetically engineered viruses and living microbes, plants, and animals may be able to reproduce and sustain themselves in the very long term. Genetic engineering has permanence. Gene therapy will alter an individual's health for life, and germline editing will affect all of a person's descendants.[122] Once Pandora's box is opened—and we have already cracked the lid—we could have little control over what happens next.

The risks of bio innovation demand a serious and considered response from governments, scientists, regulators, and society. One complication here is that jurisdictional norms vary, as do the overall approaches to risk, risk prevention, and competition. New thinking is needed, perhaps drawing on how previous waves of technology with significant associated risks, including recombinant DNA experimentation in the field of biology itself, have been handled.[123]

Biology is self-replicating, is self-sustaining, and does not respect jurisdictional boundaries

In a bid to combat the loss of life caused by the spread of infectious diseases, scientists have been developing gene drives that permanently alter the genes of the vectors (like mosquitoes in the case of malaria) that spread those diseases. The benefits to global public health could be enormous, but there could be unforeseen and uncontrollable consequences. Gene drives released into the wild can affect an entire ecosystem. Moreover, genetically altered viruses and living microbes, plants, and animals may be able to reproduce and sustain themselves into the very long term. For instance, gene-edited mosquitoes are now breeding in Brazil despite the fact that the intention of researchers had been that all released mosquitoes and their offspring should have died.[124] Although the aim of gene drives is for "useful" genetic engineering to spread through generations, this ability to spread and self-sustain is, in itself, a risk. One scientist has posited that there could be a negative impact on human health if the malaria parasite were to evolve to become more virulent or even be carried by a host other than the mosquito.[125]

[122] Germline editing is gene editing of an embryo, egg, or sperm such that changes are inherited by all future generations.
[123] Paul Berg et al., "Summary statement of the Asilomar Conference on recombinant DNA molecules," *Proceedings of the National Academy of Sciences*, June 1975, Volume 72, Number 6.
[124] *Genetically modified mosquitoes breed in Brazil*, DW, www.dw.com/en/genetically-modified-mosquitoes-breed-in-brazil/a-50414340.
[125] Megan Scudellari, "Self-destructing mosquitoes and sterilized rodents: The promise of gene drives," *Nature*, July 9, 2019.

The National Academy of Sciences has warned that "considerable gaps in knowledge" remain about gene drives' ecological and evolutionary effects.[126] Some efforts are under way to cope with challenges and better understand risks. For example, rules to govern the transfer of gene drives from the laboratory into future field tests and wider use are being developed.[127] In addition, precautions against the accidental release of gene drives are being put in place, including, for instance, systems to limit the spread of gene drives only to the populations targeted.[128] The risks of unanticipated effects can also be reduced by progressive evaluation from laboratory to field cages prior to open-field trial in isolated populations, allowing for systematic assessment of possible environmental effects under increasingly natural conditions. A team called Target Malaria working in Italy has introduced changing environmental conditions to field cages and developing ecological models so that researchers can better explore the benefits and risks of wild releases in a safe but effective way.[129]

Genetic editing of plants and animals raises the risk of outcrossing—the potential of mixing engineered genes into wild populations and native species—and potential reduction in the biodiversity of plants and animals.[130]

The interconnected nature of biology can increase the potential for unintended consequences

Biology is personal in that its foundation is built on some of the most fundamental units in our bodies, DNA, yet it is also highly interconnected. Changes to one part of the system can have cascading effects and unintended consequences across entire ecosystems or species. Even legitimate and well-intentioned use of biological technologies carries systemic risk. Successful gene editing, for instance, could have "off-target" effects beyond those intended. "Off-target" mutations have been observed for all classes of genome editing tools used to date, including CRISPR.[131] It is not yet known whether genetic engineering applied to sperm, eggs, or embryos could have unintended negative consequences if passed down through generations.

Gene therapies offered to consumers may have side effects and unknown long-term consequences that are not properly understood today. Such therapies need to be proven safe and effective in animal models before they can be tested in humans, let alone approved for treatments.

Low barriers to entry open the door to potential misuse with potentially serious—even fatal—consequences

Unlike nuclear materials, some biological technologies are relatively cheap and accessible. There is today a thriving community of "biohackers" who practice synthetic biology or CRISPR genome editing in community labs or on their own as a hobby. The Netflix documentary series *Unnatural Selection,* which had its premiere in October 2019, highlights some examples, including an individual selling $100 CRISPR kits from his garage and a biohacker who injected himself in a DIY gene edit.[132] Commercial kits to perform CRISPR alterations are sold

[126] *Report in brief: Gene drives on the horizon: Advancing science, navigating uncertainty, and aligning research with public values*, National Academies of Sciences, Engineering, and Medicine, 2016.

[127] Stephanie James et al., "Pathway to deployment of gene drive mosquitoes as a potential biocontrol tool for elimination of malaria in sub-Saharan Africa: Recommendations of a scientific working group," *American Journal of Tropical Medicine and Hygiene*, June 2018, Volume 98, Issue 6 Supplement; and "Gene-drive technology needs thorough scrutiny," *Nature*, December 5, 2017.

[128] Dominique Brossard et al., "Promises and perils of gene drives: Navigating the communication of complex, post-normal science," *Proceedings of the National Academy of Science*s, April 2019, Volume 116, Number 16.

[129] Megan Scudellari, "Self-destructing mosquitoes and sterilized rodents: The promise of gene drives," *Nature*, July 9, 2019.

[130] Outcrossing is the transfer of genes from genetically engineered plants into conventional crops or related species in the wild.

[131] Yong Cheng and Shengdar Q. Tsai, "Illuminating the genome-wide activity of genome editors for safe and effective therapeutics," *Genome Biology*, December 2018, Volume 19; Dana Carroll, "Collateral damage: Benchmarking off-target effects in genome editing," *Genome Biology*, June 2019, Volume 20; and *Nature Medicine*, "Editorial: Keep off-target effects in focus," August 2018, Volume 24.

[132] Sigal Samuel, "A celebrity biohacker who sells DIY gene-editing kits is under investigation," Vox, May 19, 2019; and Sarah Zhang, "A biohacker regrets publicly injecting himself with CRISPR," *The Atlantic*, February 20, 2018.

commercially on the internet. So far, these movements have appeared to be harmless, but nobody can guarantee that a hobby won't turn into something more sinister. There does now appear to be some regulatory scrutiny in this area.[133]

Nevertheless, the risk exists that technologies such as those used to edit microbes or viruses could be misused by people with hostile motivations or without a sufficient sense of responsibility. An individual with some specialized knowledge could, for example, create a virus tailored to specific people based on information in their genome.[134] Unlike, for example, an attempt to buy nuclear materials, purchasing the components needed to create such a tool would not raise red flags with regulators. The cost of eradicating a virus is exorbitant. In the case of smallpox, one of the deadliest diseases in history, it took decades and cost billions of dollars.[135] Yet resurrecting an extinct virus could be relatively inexpensive and simple. One small team of Canadian researchers reconstituted an extinct poxvirus—against which vaccinations had ended years ago—in 2017 at a cost of about $100,000 using mail-order DNA. Yet consider the cost of eradicating such pathogens.

Low barriers could also raise the risk of unethical corporate practices, for example if companies were to commercialize biology-based products or services before the relevant science has been fully tested and validated.

Differing value systems make it hard to forge consensus, including on life-and-death issues

Scientific advances are raising significant ethical questions. Embryo screening, selection, and editing could lead to human traits being artificially selected, raising enormous concerns. For example, the ability to edit out disabilities before birth may be seen as "playing God." Where should the line be drawn? Is it right to edit the genome of an embryo to prevent sickle cell anemia, but wrong to choose a baby's skin or eye color? Finding common answers to such questions is challenging because differing value systems are involved—at the individual, cultural, and national levels. Technical and scientific issues like embryo editing quickly become moral questions.

In the—arguably far—future, it may be possible to use genetic data to calibrate education and training programs, but this raises significant ethical issues. Even suggesting that children's education or workers' training should be based on their genes raises red flags. Not only could such approaches be interpreted as social determinism, but they risk reinforcing inequality.

Societal norms and acceptance differ between cultures and countries, guided by a range of religious, ethical, cultural, and historical values. Scientific advances in some sensitive areas may be shunned by some countries but viewed as a unique competitive advantage for businesses or economies in others, with the potential commercial gains overriding the desirability of unified regulation.

Privacy and consent issues are fundamental in this deeply intimate sphere

Concerns about personal privacy and consent in the digital age are debated widely. There is already a popular backlash against the gathering of private data about shopping habits, for instance. This discomfort about data mining could be much greater in the case of biological uses because the data being gathered couldn't be more personal—from our bodies and minds. Omics data is so information-rich that, even when it is anonymized and aggregated,

[133] *Information about self-administration of gene therapy*, US Food and Drug Administration.
[134] Andrew Hessel, Marc Goodman, and Steven Kotler, "Hacking the president's DNA," *The Atlantic*, November 2012.
[135] Kai Kupberschmidt, "How Canadian researchers reconstituted an extinct poxvirus for $100,00 using mail-order DNA," *Science*, July 6, 2017.

individuals may still be identifiable, and sensitive personal or medical information could be exposed.

The explosion of available biological data is fueling innovation, but concern is widespread. In the United States, so many individuals had taken DTC genetic tests that it was possible to access material from open databases and identify about 60 percent of Americans with European ancestry from a DNA sample as of late 2018.[136] This prompted some DTC companies to tighten up the availability of such data.[137] Some individuals identified through these methods never gave consent or received genetic testing themselves; rather, their family members did. There are also consent concerns with newborn testing, to which parents agreed on their children's behalf, but the data can affect the individuals all their lives. Finally, we are all familiar with data regulations that require us to click on the "accept" button on all the websites we visit to give consent to our data being gathered.[138] But consumers are not always informed about how their DNA—gathered during a genetic test—is shared with third parties. This has led to some DTC genetic testing companies separating consent to be tested from consent to the storage, use, and sale of test results.

Citizens' privacy may not be protected when law enforcement agencies ask for data. FamilyTreeDNA had to apologize for not disclosing an agreement with the FBI that gave the bureau routine access to its database. In the aftermath, the company decided to introduce an opting-out choice to customers.[139] Improved DNA sequencing led to the capture of the so-called Golden State Killer in 2018, but the case highlighted consent issues. After the case, GEDMatch changed its privacy policy to limit law enforcement access only to profiles of users who have given permission; this led to a 95 percent reduction in profiles available to police.[140] Governments and security agencies are already grappling with the need to balance security with citizens' privacy rights. It is possible that members of the public will be even less comfortable with their government holding their DNA than with private companies doing so.

In the future, there may be more sophisticated headsets that read brain signals and can discern a patient's mental state, a potentially useful tool in therapy. In 2013, Carnegie Mellon University researchers reported monitoring subjects' mental states using a machine that recognized the emotions they experienced to a reasonable level of accuracy.[141] Theoretically, such a machine could be used in law enforcement and in the courts to read a person's emotional reaction to questioning or an evidentiary statement—a new lie detector. But this use of the technology appears to represent a significant invasion of privacy. Some biomachine interface technologies could even pose risks to national security. The ability to read brain signals in brain-based communications could result in unintentional transmission of sensitive information or national intelligence. Surgically implanted brain-computer interfaces could pose a security threat if hackers are able to invade the systems and hijack individuals' behavior or action.

Unequal access could perpetuate socioeconomic disparities, with potentially regressive effects

Biological advances and their impact on economies and societies could reinforce and widen inequality between the wealthy and less well-off within countries, and between nations.

136 Jocelyn Kaiser, "We will find you: DNA search used to nab Golden State Killer can home in on about 60% of white Americans," *Science*, October 11, 2018.
137 Heather Murphy, "Most white Americans' DNA can be identified through genealogy databases," *New York Times*, October 11, 2018.
138 An example of such regulations is the General Data Protection Regulation that came into force in the European Union in May 2018. See *EU data protection rules*, European Commission, https://ec.europa.eu/info/priorities/justice-and-fundamental-rights/data-protection/2018-reform-eu-data-protection-rules/eu-data-protection-rules_en#abouttheregulationanddataprotection.
139 Rachel England, "Family Tree DNA will let customers opt-out of the FBI's genetic data access," Engadget, March 14, 2019.
140 Terry Spencer, "Police use of DNA leads to backlash, changes to big database," Associated Press, June 7, 2019.
141 Jennifer Kite-Powell, "Using brain signals to read emotions," *Forbes*, June 25, 2013; and *Carnegie Mellon researchers identify emotions based on brain activity*, Carnegie Mellon University, June 19, 2013.

The changes are advancing quickest and most broadly in relatively rich countries, and there is a danger that these technologies could be heavily concentrated in countries with the means to invest in their development. Adoption of healthcare-related omics and molecular technologies varies enormously among countries. It is happening in high-income countries as well as China, which is ahead of developed economies on the advancement and adoption of some of these innovative technologies.[142] In the case of CAR T-cell research, for example, more active trials are being held in China than in the European Union (EU), Japan, and the United States combined.[143] Overall, our analysis finds that countries with high readings on the socio-demographic index account for roughly 30 percent of today's global disease burden (the number of individuals with sickle cell anemia is highest in Africa, for example), but those countries could gain about 70 percent of the total reduction in the global disease burden from the deployment of biological advances.[144] This reflects the high price of, and the need for, specialized infrastructure, supply chains, and talent to support innovative treatments such as CAR T-cell therapies.

Within countries, access to beneficial biological applications may be open only to the wealthy given that many of the applications remain expensive. Neuroprosthetics are biomachine interfaces where limbs are controlled with considerable precision by linking up directly to, and reading, brain signals. Healthcare systems in many countries may not be able to afford to offer neuroprosthetics to patients at current prices. For example, the cost of lower extremity limbs ranges from $5,000 to $50,000, and upper extremity limbs from $3,000 to $30,000.[145] A gene therapy for the treatment of spinal muscular atrophy approved for use in the United States costs $2.1 million for a single use.[146] If healthcare systems do not pay for all or some of the costs of these treatments, they will remain the preserve of the minority that is able to afford them. There is also a risk that, used or analyzed in a biased way, genetic data could discriminate against certain groups in society, including women and different ethnic groups.[147] This built-in bias could mean that patients are treated differently when matched to providers, with a knock-on effect on insurance premiums and employment.

Finally, biological applications that edit out "less desirable" traits could lead to outcomes that are regressive and disenfranchise marginalized groups. Many genetic mutations result in conditions that society considers to be disorders or health complications and that form a core part of a group's identity (for instance, achondroplasia or dwarfism). Any developments that purport to "fix" the genetic mutations experienced by these groups may seem demeaning.

These issues demand a considered response and, potentially, new approaches to safeguarding and oversight

The unique risks and issues raised by biological advances demand a considered response. In the case of past technological innovation, governments, scientists, and regulators often arrived at risk-management systems in response to crises. In this case, however, given the persistence and severity of the risks, a wait-and-see attitude and experimentation may not be sufficient. New approaches could be needed. Regulation is an important part of the necessary response, but not the whole story. Systems are needed to detect, monitor, and intervene in scientific developments. Scientists themselves can play a role in building safeguards into new biological technologies.[148]

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142 Preetika Rana, Amy Dockser Marcus, and Wenxin Fan, "China, unhampered by rules, races ahead in gene-editing trials," *Wall Street Journal*, January 21, 2018.

143 This is based on our review of Clinicaltrials.gov in 2019. Our search covered ongoing trials for CAR, CAR-T, and chimeric antigen receptors.

144 The socio-demographic index is a development classification system specific to the Institute for Health Metrics and Evaluation (IHME) based on metrics such as per capita income and average years of schooling. Figures given are based on the IHME Global Burden of Disease 2017.

145 Rhonda Turner, "Prosthetics costs: The high price of prosthetic limbs," *Disabled World*, May 5, 2009.

146 *AveXis announces innovative Zolgensma gene therapy access programs for US payers and families*, Novartis, May 24, 2019.

147 Ziad Obermeyer et al., "Dissecting racial bias in an algorithm used to manage the health of populations," *Science*, October 2019, Volume 366, Issue 6464.

148 Jackson Champer et al., "Molecular safeguarding of CRISPR gene drive experiments," *eLife*, January 22, 2019.

Any response to the risks that is purely national might not be effective, given the ineluctable fact that biology does not respect borders—a gene drive approved and conducted in one country may affect neighboring countries with or without their consent—and there are already signs of regulation unfolding unevenly in jurisdictions with multiple value systems.

That said, developing national standards is an important first step. In the United Kingdom, the independent Nuffield Council on Bioethics was set up in 1991 to provide advice to policy makers and stimulate public debate on bioethics. Since 1994, it has been funded jointly by the Nuffield Foundation, Wellcome, and the Medical Research Council.[149] The Parliamentary Office of Science and Technology takes a role in overseeing advances in biology, including genetic engineering.[150] In the United States, President Barack Obama convened a commission for the study of bioethical issues to explore and set ethical boundaries. The commission identified five ethical principles: public beneficence, responsible stewardship, intellectual freedom and responsibility, democratic deliberation, and justice and fairness.[151]

However, without global standards and agreements, there is still a risk of a biological regulatory "race to the bottom" with some governments taking a more laissez-faire approach to ethical considerations for competitive reasons, putting pressure on more cautious governments to follow suit. Many countries are signatories to the Biological Weapons Convention, but not all nations are equally bound by similar codes of conduct outside of the use of biology for weapons, and some may continue to take different regulatory approaches in this area. Global consensus on standards may prove difficult to achieve.

Governments, regulators, and the scientific community need to be proactive in engaging with the public.[152] Citizens on the ground will need to have an informed opinion about the trade-offs they are prepared or not prepared to accept and will need their voices heard. The view of those trade-offs may well vary. For instance, citizens of a country where malaria continues to affect many lives may be more willing to accept gene-edited organisms. Engaging with the public too late can have serious repercussions. Some work has already been done on the benefits of real-time technology assessment, anticipatory governance, and upstream engagement.[153]

Arguably, the global scientific community has already been more proactive on the potential hazards of bio innovation than on nuclear physics and AI. In 1975, the Asilomar Conference convened an international group of mostly scientists to review scientific progress in research on recombinant DNA molecules and discuss ways of dealing with the potential biohazards the work could entail.[154] Regulation and oversight need to be adaptable, responding to technological breakthroughs as they happen—or, ideally, anticipating them.

New tools to oversee science as it develops are necessary. One idea is to ensure that all research studies that have been vetted for ethical content are placed in an open registry. Another is for researchers to develop an early-warning system that enables them to report any research that risks overstepping ethical boundaries. One approach that could be borrowed from AI—which has its own ethical challenges—is for "red teams" of academics,

149 Nuffield Council on Bioethics.

150 Peter Border and Louise Connell, *Regulation of synthetic biology*, UK Parliamentary Office of Synthetic Biology, June 2015.

151 *New directions: The ethics of synthetic biology and emerging technologies*, US Presidential Commission for the Study of Bioethical Issues, December 2010.

152 *Gene drives on the horizon: Advancing science, navigating uncertainty, and aligning research with public values*, National Academies of Sciences, Engineering, and Medicine, Washington, DC: The National Academies Press, 2016.

153 David H. Guston and Daniel Sarewitz, "Real-time technology assessment," *Technology in Society*, 2002, Volume 24, Issues 1–2; Daniel Sarewitz, "Anticipatory governance of emerging technologies," in *The growing gap between emerging technologies and legal-ethic oversight*, Volume 7, Gary B. Marchant, Braden R. Allenby, and Joseph R. Herkert, eds., Dordrecht, Netherlands: Springer, 2011; James Wildson and Rebeca Willis, *See-through science: Why public engagement needs to move upstream*, Demos, 2004; and Jennifer Kuzma, James Romanchek, and Adam Kokotovich, "Upstream oversight assessment for agrifood nanotechnology: A case studies approach," *Risk Analysis*, August 2008, Volume 28, Issue 4.

154 Paul Berg et al., "Summary statement of the Asilomar Conference on recombinant DNA molecules," *Proceedings of the National Academy of Sciences*, June 1975, Volume 72, Number 6.

ethicists, and practitioners to audit and review models before they are deployed.[155] The same approach could be applied to biological applications, such as new genetically engineered strains of crops or animals, when they move from the lab to the field. Research institutions and funders should define and then monitor clear protocols.[156] In many cases, an interdisciplinary approach will be necessary given that these issues—gene drives included—go beyond the technical to social, ethical, and legal dimensions.

The many risks that come with advances in biology raise significant questions for citizens and regulators. They could be one of the most formidable barriers to the progress of biological advances. Careful thinking will be needed about the tools and tactics, including potential new approaches, that may be required to mitigate or minimize certain types of risk. The next chapter turns to scenarios for the adoption of applications and their impact in the near and longer term.

[155] Jake Silberg and James Manyika, *Tackling bias in artificial intelligence (and in humans)*, McKinsey & Company, June 2019.

[156] "Germline gene-editing research needs rules," *Nature*, March 13, 2019.

Man wearing brainwave scanning headset in modern neurological research laboratory
© Slavemotion/E+/Getty Images

4. The path to adoption and impact

The speed with which biological applications move from the lab to commercial adoption will depend on many factors, including the progress of scientific research, whether the economics of a particular application work, and how weak or strong public and regulatory acceptance proves to be.

The journey to adoption may take years for many applications. Nevertheless, major progress is being made. For this research, we examined a wide range of specific areas of application and compiled a library of about 400 use cases, most of which are scientifically feasible today and which could have economic impact in the next ten to 20 years. The library is not exhaustive, but it nonetheless provides some idea of the pipeline for the years ahead. The impact could potentially be even higher for a number of reasons, including spillover effects across the economy.

In this chapter, we examine and seek to assess the potential impact of these applications over the next three decades, based on our analysis of the use case library. We also examine the factors that could speed up or slow down their journey to adoption.

A visible pipeline of applications could have broad impact in ten to 20 years, with more beyond

While biological sciences have been evolving for years, they have now reached a new phase of growth at which applications have sufficient scientific underpinnings and compelling enough economics for us to anticipate adoption that produces economic impact within the next ten to 20 years. This will be only one wave of impact. The impact is likely to be larger as it spreads upstream, downstream, and to ancillary players, potentially transforming value chains, and catalyzing the creation of new business models and players in nearly all sectors.

Biological applications could unlock an estimated $2 trillion to $4 trillion in annual direct global economic impact

We gathered about 400 detailed use cases that employ elements of biological technologies—or look likely to do so in the future. We surveyed these applications by examining the visible pipeline of relevant applications, from publications such as research papers. We then tested the applications with a variety of scientific and industry experts. The direct economic impact of each use case depends on adoption volume and value gain. We assessed four drivers of value gains: reduced disease burden translated to economic productivity, greater willingness to pay more for improved quality, cost productivity, and environmental benefit (see Box 2, “Estimating potential direct economic value,” and the technical appendix for full details of the methodology). Taken together, we estimate that over the next ten to 20 years, biological applications could have direct annual economic impact of between about $2 trillion and $4 trillion globally (Exhibit 7).

Box 2

Estimating potential direct economic value

The library of about 400 use cases compiled for this research is a visible pipeline of innovations under way and lying ahead. To compile the library, we first defined which technologies fell within the scope of the Bio Revolution as defined in this research. We then identified a pipeline of applications that could produce tangible benefits from those emerging technologies. The library includes use cases that are scientifically conceivable today and could plausibly be adopted by 2050. It excludes applications that are not scientifically conceivable today (for instance, steel production via biological means) or are unlikely to have material impact by 2050. All technologies described in chapter 1 are included. We excluded technologies that are already commercially mature. We tested the use cases with a range of experts to better understand economic potential and adoption timing.

This library, while extensive, is not exhaustive. For instance, there are applications that we cannot identify today due to limited public information—many innovations are being developed in private labs or in the defense industry, where developments remain confidential for commercial or national security reasons. In addition, while we sought input from a wide range of experts, that input was not exhaustive.

To estimate the tangible impact of these applications (which is expressed in annual global terms relative to the 2020 economy), we focused on use cases in biology-centric domains where core products or services could be inherently biological (Exhibit 6). Domains include multiple sectors, such as human health and performance, which includes both healthcare systems and services and pharmaceutical and medical products. We then estimated the direct impact by sizing four value gain drivers: reduced disease burden translated to economic productivity, improved quality (expressed through greater willingness to pay), cost productivity (for instance, incremental cost saving to make products), and environmental benefit (from reduced greenhouse gas emissions).

Using expert input and historical analogs, we extrapolated our assessed impact to different time horizons by estimating how long it might take for an application to achieve scientific feasibility, commercial availability, and then peak impact. We acknowledge that adoption levels and timing may be subject to many uncertainties, including shifting product features and customer demographics, that may not be fully captured in our assessment. Adoption was modeled based on innovation-adoption curves that varied depending on the type of use case to allocate the impact to different time horizons.

Exhibit 6

Overview of methodology for estimating direct economic impacts.

Scope and factors in our assessment	Included	Excluded
Technology Applicability	• Mapping and engineering of biomolecules, biosystems, biomachine interfaces, and biocomputing	• Mature technologies out of scope (eg, small molecules, biologics, genetically modified crops)
Development phase Maturity of use cases	• Scientifically conceivable today and plausibly commercialized by 2050 (eg, CAR-T therapies for solid tumors) • Use cases that are not yet scientifically feasible and are still in research phases (eg, microbiome-based skin-care products)	• Not yet scientifically conceivable today (eg, steel production via biological means) • Unlikely to have material economic impact by 2050 (eg, biology-based parallel computing)
Domains Cluster of sectors	• Direct biology-centric domains where core product or service could be inherently biological, such as the following sectors: healthcare systems and services, pharmaceuticals and medical products, agriculture, consumer goods and services, basic materials manufacturing, and energy	• Other sectors not inherently biological that experience indirect impact (eg, upstream, downstream, ancillary), including insurance, entertainment, finance
Impact Value gain drivers	• Value gain drivers of direct impact estimated – Reduced disease burden translated to economic productivity – Improved quality, measured by greater willingness to pay – Cost productivity (eg, incremental cost saving to produce product) – Environmental benefit (from reduced greenhouse gas emissions)	• Knock-on effects, such as reduced agricultural land use from shifting to alternative proteins or changes to life insurance from longer life spans • Broader societal impact, such as effects on inequality or population phenotype

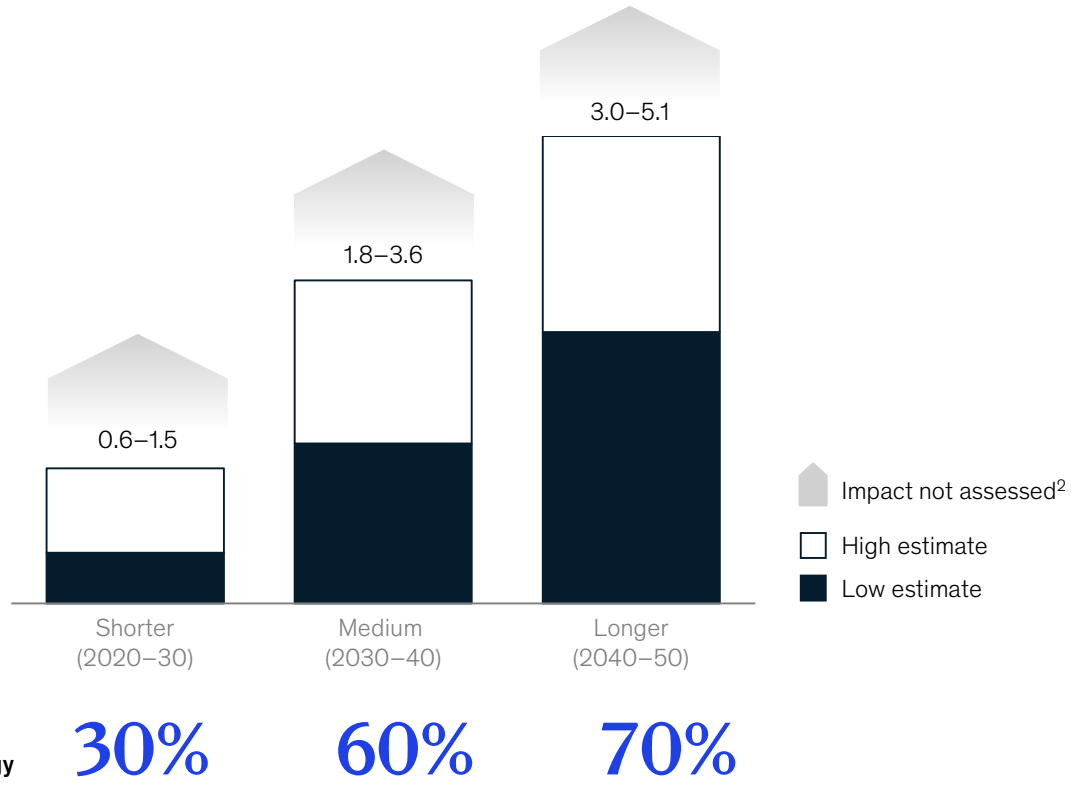
Source: McKinsey Global Institute analysis

Exhibit 7

In ten to 20 years, a visible pipeline of biological applications could create approximately $2 trillion to $4 trillion of direct annual economic impact.

Partial estimate of potential and direct annual impact by time horizon[1]

$ trillion



1. Current figures are based on potential direct annual economic impacts from 400 use cases examined, excluding non-omic economic impact from biocomputing and half of the biomachine applications.
2. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.

Source: McKinsey Global Institute analysis

All applications with economic potential in the next decade are scientifically feasible today, with the majority already commercialized in market. In the longer term, roughly 60 percent of the potential economic impact from the use cases sized is already commercially available today, with less than 15 percent not scientifically feasible today. The wide ranges in the estimates of impact reflect uncertainties about the pace and extent of commercialization and adoption.

There are two broad categories of applications: those that garner insights from the sequencing and analysis of biological data, and applications that depend on the manipulation of biology through genetic, cell, and tissue engineering.

The former—the analysis of genomic, microbiome, neural, and other biological data and the application of insights to enable precision and personalization on an unprecedented scale—will dominate impact in the short term. Faster computation and the increasing use and sophistication of analytics and AI will make it possible to derive more insights from biological data and predict biological associations and processes. In agriculture, tapping into large libraries of genetic and microbe data will likely enable farming to be tailored for desired

outcomes under distinct local conditions in specific sites. Using similar data pools, products and services can be tailored to the genetic profile and microbiome composition of consumers. Indeed, over the next ten years, even if there are no further advances in the ways that biology is engineered, an enormous amount of value can be created purely by analyzing the exploding amount of biological data now being gathered. We estimate that this could amount to between about $400 billion and $900 billion, more than half of the total potential direct impact.

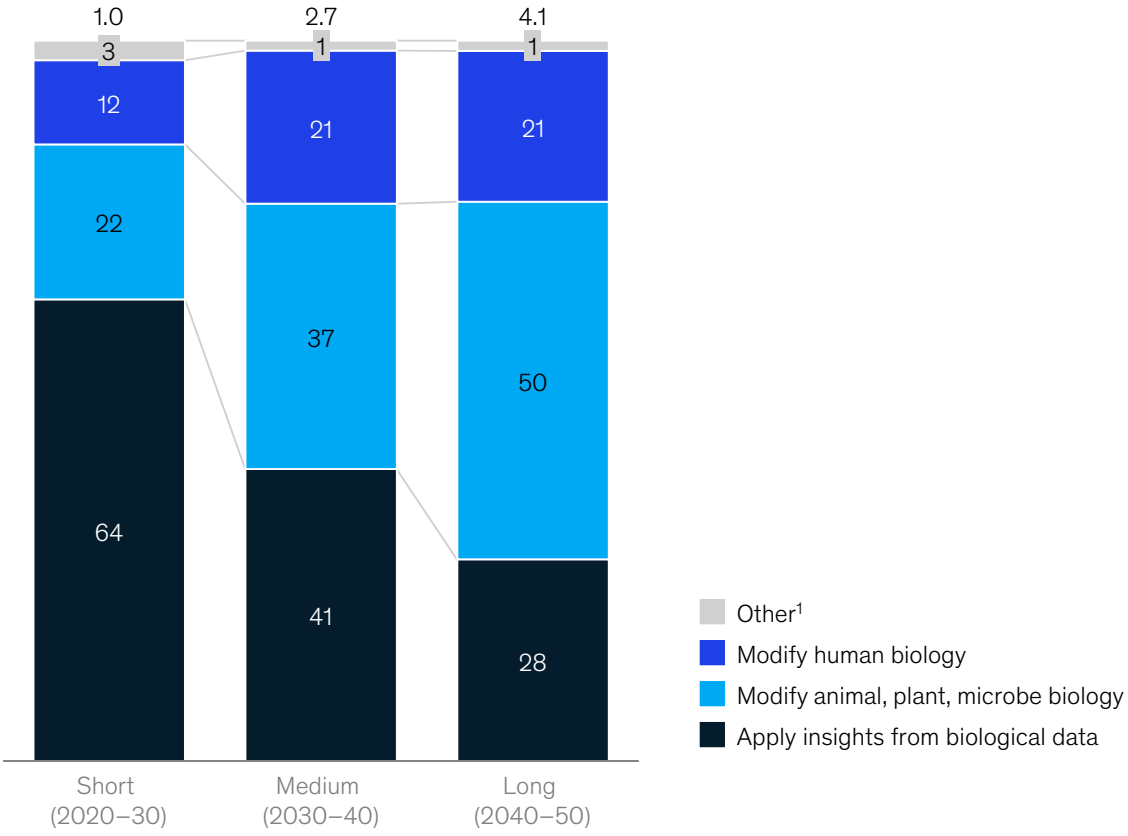
However, it is likely that impact from the second type of application—engineering biology—will grow faster. As scientific (and regulatory and commercial) challenges are overcome, techniques to engineer biology such as CRISPR will add to the value that is already being created through biological data analysis (Exhibit 8). By the medium term—from 2030 to 2040—the tables will have turned, and biological engineering could account for the majority of the overall direct annual impact, about 60 percent. We estimate that the impact could amount to between about $900 billion and $2.2 trillion per year.

Exhibit 8

Applications based on insights from biological data make up the biggest share of economic impact created in the short term.

Sized applications by technology platform (partial estimate)

%; $ trillion



1. Read brain states to control external equipment, synthesize DNA, proteins, microbes.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.

Source: McKinsey Global Institute analysis

The most direct impact will appear in life science and human-centric domains

Human health and performance have the most scientific advances and the clearest pipeline from research to application. The science is advanced, and the market is generally accepting of innovations. However, based on our use cases, the impact could be far more broad-based: in the next ten to 20 years, more than half of the direct impact is likely to be outside health, primarily in agriculture and consumer products.

Our use case library suggests that most value related to bio innovations in the next one to two decades will come in four domains, or clusters of sectors where many applications are emerging from bio innovation. The four are human health and performance; agriculture, aquaculture, and food; consumer products and services; and materials, chemicals, and energy. The ranges of impact, and shares of impact, in human health and performance and in consumer products and services includes some impact from biomachine interfaces. Applications in some other sectors could also be on the path to adoption, including in the areas of undoing environmental harm, education, security, and space exploration (Exhibit 9).

— **Human health and performance.** Applications include cell, gene, and RNA therapies to treat or even prevent disease, a range of anti-aging treatments to extend life spans, innovations in reproductive medicine, and improvements to drug development and delivery. The impact here could amount to between $500 billion and $1.3 trillion over the next ten to 20 years, or 35 percent of the overall impact that we estimate for this period. The greatest potential source of value is increased workforce productivity from a reduction in the global burden of disease, due to advances in preventing, diagnosing, and treating diseases (notably cancer and infectious diseases) and in anti-aging therapies. We estimate between 1 and 3 percent of the total global burden of disease could be reduced in the next ten to 20 years from these applications—roughly the equivalent of eliminating the global disease burden of lung cancer, breast cancer, and prostate cancer combined. Such advances could have significant spillover effects on other industries. For instance, longer life spans could affect the life insurance industry. Adoption of applications and therefore the timing of impact will vary. Shorter-term impact is expected from reducing the disease burden from therapeutic areas where cell and gene therapies already exist, including, for instance, treatments for certain types of monogenic diseases and cancer. In the longer term, innovations are likely to spread to more therapeutic areas such as cardiovascular and neurodegenerative diseases. Anti-aging therapies may also come to fruition in the longer term. In reproductive medicine, genetic screening of parents and embryos for certain medical conditions already exists. In the longer term, embryo editing for medical purposes could emerge. Practically all of the impact in human health is influenced by accelerated research as well as genetic-level personalization and precision.

— **Agriculture, aquaculture, and food.** Applications include innovative ways to conduct marker-assisted breeding of animals and plants using genetic markers that are many times quicker than traditional selective breeding methods; new, more precise tools for the genetic engineering of plants (that is, without introducing foreign genetic materials); fast-developing work using the microbiome of plants, soil, animals, and water to improve the quality and productivity of agricultural production; and the development of alternative proteins, including lab-grown meat. Annual direct impact could be an estimated $800 billion to $1.2 trillion over the next ten to 20 years, or 36 percent of the total. The greatest impact may well come from marker-assisted breeding, genetic engineering of plant and animal traits, microbiome mapping and modification, and alternative proteins. Innovation in crop and livestock farming has helped feed the world, and the bio innovations now being commercialized build on this by giving us new tools to meet ever more pressing challenges in ensuring food security for a growing global population and managing depleting natural resources more sustainably. Global food systems are relevant to all of

the United Nations Sustainable Development Goals.[157] The science is progressing quickly, but consumer reaction and regulatory constraints are the bigger barriers in some regions. In the short term, impact is expected from the application of insights from biological data to measure food safety and quality and to improve selective breeding decisions. Novel plant-based meats may see some adoption. In the medium term, there could be a range of genetically engineered traits with CRISPR in plants as well as impact from screening the microbiome in agricultural production and subsequently optimizing the use of agricultural inputs. Cultured meat could also hit the market. In addition, there could be impact from genetically engineered traits with CRISPR in animals, potentially faster in some regions than others, depending on the regulatory stance.

— **Consumer products and services.** Opportunities are opening up to use increasing volumes of biological data to offer consumers personalized products and services based on their biological makeup. Applications include DTC genetic and microbiome testing, beauty and personal care increasingly based on greater knowledge of the microbiome as testing spreads, and innovative approaches to wellness, including fitness and nutrition, not only in humans but in pets.[158] Annual economic impact over the next ten to 20 years could be between $200 billion and $800 billion, or 19 percent of the total. Roughly two-thirds of the impact is driven by personalization, demonstrating the core importance of tailoring to impact. The largest impact in this domain comes from wellness applications related to monitoring nutrition, fitness, and personal health based on omics data, and personalized probiotics and vitamins. In the short term, impact is expected from insights based on DTC genetic and microbiome testing that enables personalization of related products and services for both consumers and pets. In the medium term, there could be improvements in wellness applications such as personalized fitness and diet based on new ways to measure omics and other biological data in a noninvasive manner. In the longer term, depending on funding and regulation, impact could come from nonmedical gene therapies for cosmetic uses.

— **Materials, chemicals, and energy.** Bio innovations could help to improve how these physical inputs are produced, in some cases substituting or complementing existing products with new ones that have improved performance or novel characteristics that offer societal benefits—often more sustainably. Applications include innovations related to materials production, such as improved fermentation processes, new bioroutes utilizing the ability to edit the DNA of microbes to develop novel materials with entirely new properties (self-repairing fabrics are one example; another is making leather using mushrooms instead of animal hide), and building on advances in biofuels to innovate new forms of energy storage. Over the next ten to 20 years, this domain could account for direct impact of $200 billion to $300 billion a year, or 8 percent of the total. The greatest potential source of value is efficiency (cost savings) in the production of materials such as nylon, silk, cotton, and clothing dyes using fermentation due to improved fermentation processes and new bioroutes. Our assumptions about impact in this domain are conservative because promised innovation in the past has not materialized and because it is not known what novel materials will be developed. In the short term, impact is expected from increased efficiency in existing fermentation processes and potential new bioroutes to creating existing materials such as fabrics and food and feed ingredients. In the medium term, there may be impact from the production of completely novel materials. In the longer term, applications such as biobatteries could emerge.

[157] *Innovation with a purpose: The role of technology innovation in accelerating food systems transformation*, World Economic Forum in collaboration with McKinsey & Company, January 2018.

[158] We include wellness, nutrition, and fitness in consumer products and services rather than health because they tend not be mediated by healthcare professionals but consumed directly by individuals, and are subject to choice—consumers choose to consume biological products and services such as skin and beauty products and DTC testing. While some consumer applications, including, for instance, consumer wearables, may have impact on the disease burden, they are not direct treatments or therapies.

— **Sustainability and other applications.** Beyond these four core areas, we found a range of potential applications in other sectors, including environmental management, education, security, and space exploration. Applications include biosequestration and bioremediation that could help to address environmental challenges, the enhanced use of DNA sequencing for solving crimes, and potentially personalized learning using genetic profiles. In all, we estimate that applications in sustainability, education, and security (we did not size the potential in defense) could have a total impact of between about $25 billion and $45 billion over the next ten to 20 years, or less than 1 percent of the total impact in that time frame, although the potential could be greater further out. Of these applications, some with the most potential value could undo environmental harm with three categories of potential applications: bioremediation, biosequestration of CO_2, and monitoring for diversity and signs of ecological damage. Some possible applications are emerging in education, such as personalized learning programs tailored based on genomes, and in security, including, for instance, using DNA testing as biometric verification (for example, to execute financial transactions). These applications are nascent and are fraught with enormous risks and ethical concerns. Finally, bio innovations could aid space exploration by enhancing the health of astronauts and even develop habitats in space, although any economically significant impact is not likely to emerge before 2050. Overall, applications in these areas are less advanced in scientific feasibility and potential commercialization, and their adoption may face significant ethical hurdles.

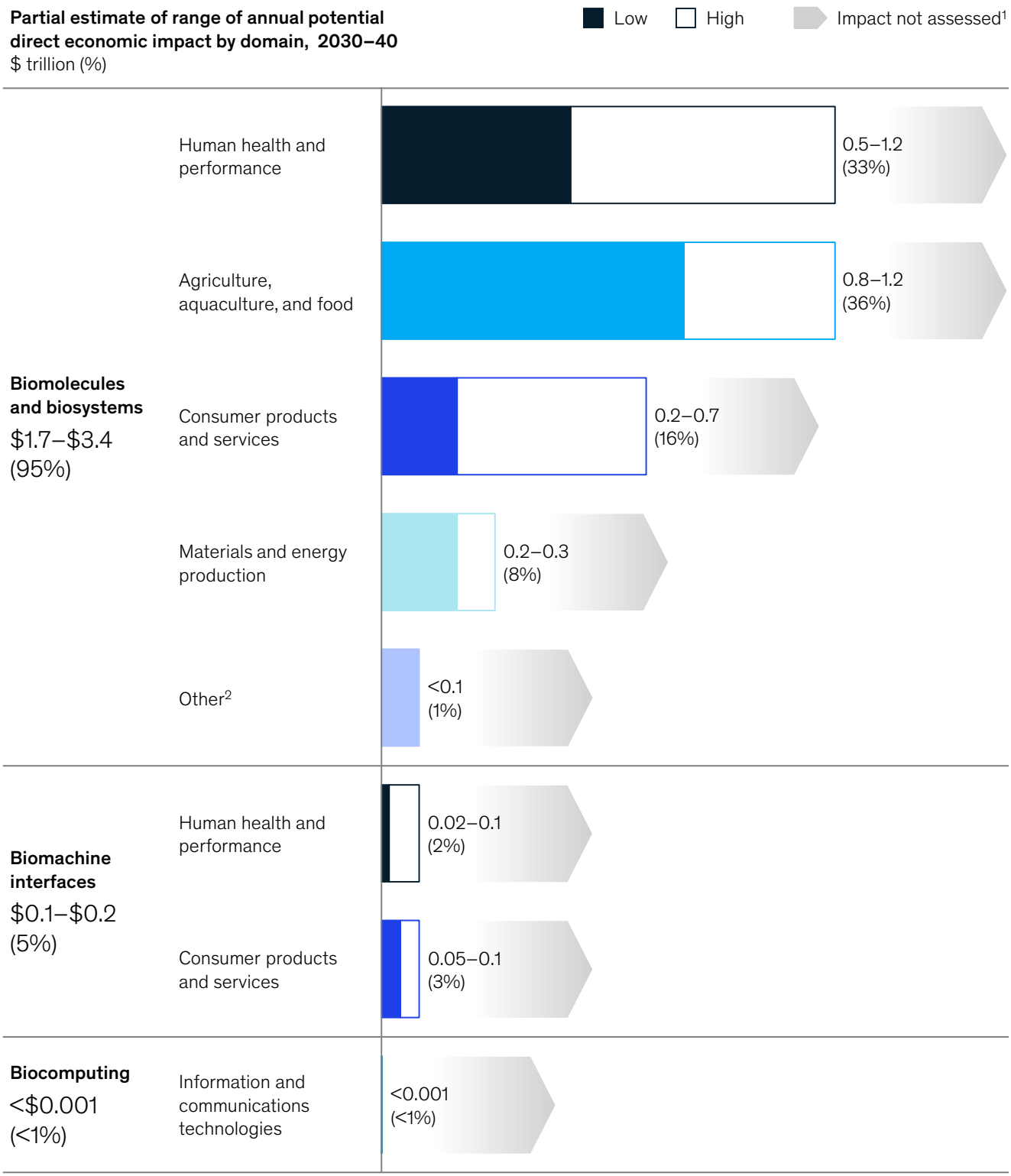
In addition to impact from applications in biomolecules and biosystems, potential impact is also emerging in biomachine interfaces and biocomputing. The science and development is at an early stage, but some applications already appear promising. The impact is likely to appear in a range of domains, including human health and performance, and in consumer products and services, but over longer time horizons.

— **Biomachine interfaces.** Over the past decade, the development of more complex and advanced algorithms and systems has made possible the development of biomachine interfaces—between brains and computers. Over the next ten to 20 years, the annual impact could range between about $70 billion and $200 billion, or 5 percent of the total. In this case, biomachine interfaces could create impact in several of the domains described. For example, neuroprosthetics restoring hearing or vision would improve human health and performance. Applications such as headbands for monitoring stress levels from electric signals would apply in consumer products and services.

— **Biocomputing.** As noted in chapter 1, this field could contribute to information and communications technologies, because data could be stored on DNA. Commercially usable nucleic acid storage and biology-based parallel computing are not likely to become commercially significant before 2050 given the significant challenges that need to be overcome, such as prohibitive cost and limited speed. Nonetheless, taking a long-term view, we estimate that biocomputing applications could create impact of between $5 billion and $15 billion in the years beyond 2050.

Exhibit 9

More than half of the impact from the visible pipeline of applications is outside of healthcare—in agriculture, consumer, and other areas.



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
2. Other applications include defense and security, undoing environmental harm, and education and talent.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation. Percentage of total impact is based on the midpoint of our estimated range of annual potential direct economic impact.

Source: McKinsey Global Institute analysis

The total economic impact will be larger than the direct impact of these use cases

This direct impact estimated across the domains may be only a small portion of the potential scale of impact. Even in the near term, the impact could be larger as new scientific breakthroughs emerge and as the direct impact we note above starts to have knock-on effects or spills over to other sectors. Beyond the initial direct impact, we are likely to see a second wave that affects other sectors that are upstream, downstream, or ancillary. In the longer term, more broadly, the impact could radiate out to every sector of the economy with effects on society and the environment. Considering the visible pipeline of applications we sized in the human health domain, between 1 and 3 percent of the total global burden of disease could be reduced in the next ten to 20 years from these applications. While this near-term impact is significant, it is only a fraction of the transformational change that may be achievable. Many factors will shape the full extent of impact and the ability to capture as much of the full potential as possible, such as funding for basic science and treatments that can pass clinical trials and are commercially viable alternatives to existing treatments. In general, the total economic impact will exceed our estimates of the direct impact for a number of reasons (Exhibit 10). They include the following:

— **Unassessed use cases.** Our library of about 400 use cases, while extensive, is not exhaustive. We acknowledge that there are many use cases we cannot identify today due to limited public information—many innovations are being developed in private labs or in the defense industry, where developments remain confidential for commercial or national security reasons.

— **Faster and higher adoption.** A range of factors could accelerate adoption of scientific advances. Companies could help speed up time to market and adoption of some applications by increasing investment, focusing on scientific advances and technologies that are likely to have the most impact, and/or partnering with innovative startups. In addition to adoption speed, peak adoption levels may continue to increase due to factors such as shifting product features, customer preferences, and lower price. For example, we could see faster adoption or higher adoption levels of expensive therapies (for example, CAR T-cell therapy for cancer) resulting from broader insurance coverage.

— **Knock-on economic effects.** The impact of some applications could in turn have knock-on economic effects. For example, improved health could mean that people lead longer and more productive lives; a potential boost in economic contribution is one of the key components of direct economic impact we have assessed. In addition, longer lives and healthier populations have potentially far-reaching implications. Retirement ages may rise, demand for eldercare delivered in the home may also rise, and social security and pensions may need to adapt. Or, if alternative proteins replace some meat production, land now dedicated to grazing could be repurposed for conservation efforts or new commercial uses.

— **Impacts on upstream, downstream and ancillary players.** After the first wave of innovations in the domains directly affected by the bio innovations, a second wave of innovations may spill over into a broader segment of the economy, transforming value chains and encouraging new business models and players in nearly all parts of the economy. For example, in the case of applications in agriculture, aquaculture, and food, there will be innovations that diffuse into food retailing, for instance. Numerous fast-food chains have announced deals with plant-based meat-substitute producers to offer vegetarian and vegan versions of popular menu items. Logistics and transportation players may adapt to genetically engineered produce that can be kept fresh for far longer than its conventional counterparts even without being refrigerated, and to increased demand for alternative proteins. In the longer term, every domain of the economy may be affected as bio innovation transforms profit pools, value chains, and business models.

— **Existing scientific breakthroughs spur more breakthroughs.** Some innovations have the ability to generate more innovations. They do so by helping to improve existing products and processes or by inventing and implementing new ones. For example, the Human Genome Project initially set out to determine a map of the human genome. In doing so, the HGP was instrumental in pushing the development of high-throughput technologies for preparing, mapping, and sequencing DNA. The improved ability to sequence DNA has, in turn, led to sequencing of the genomes of microbes, plants, and animals, which has advanced many fields of science, including microbiology, virology, infectious disease, and plant biology. In addition, new biology and new technologies brought about by the HGP have enabled many other large-scale research initiatives to go forward. Examples include the ENCyclopedia of DNA Elements (ENCODE) research consortium, International HapMap Project, 1000 Genomes, Cancer Genome Anatomy Project, Human Microbiome Project, and Roadmap Epigenomics Project.[159]

— **New scientific breakthroughs enabling more commercial applications.** Biology research is continually developing, and more scientific breakthroughs could provide a foundation for downstream commercial applications that may become available in the next few decades. For example, before the Human Genome Project, researchers knew the genetic basis of tens of disorders. Today, they know the basis of thousands of conditions. Genomics is thus helping transform medicine. More than 100 different FDA-approved drugs are now packaged with instructions that tell doctors to test their patients for genetic variants linked to efficacy, dosages, or risky side effects.[160] Funding basic science or helping promising applications accelerate through research pipelines could directly influence the number of commercial applications in the future, beyond use cases we may have missed in our sizing.

In the longer term, biological advances could have even broader effects across society, helping to address key challenges. Health is one example; it could be improved by innovations not only in healthcare but in other sectors. One example is chemicals such as nutraceuticals and sugar replacements, which could potentially improve the health of populations. Controlling the quality of meat grown in labs may be easier than when compared with living animals, and this may reduce the negative health consequences from antibiotics and growth hormones commonly used in animal agriculture. In addition, improved accuracy and cost-effectiveness of DNA sequencing, leading to widespread adoption, may reduce foodborne illnesses and allergic reactions. Personal insights into health risks and lifestyle aspects such as fitness and nutrition could improve the health of populations via personalized fitness and diet.

[159] Leroy Hood and Lee Rowen, "The Human Genome Project: Big science transforms biology and medicine," *Genome Medicine*, 2013, Volume 5, Number 79.

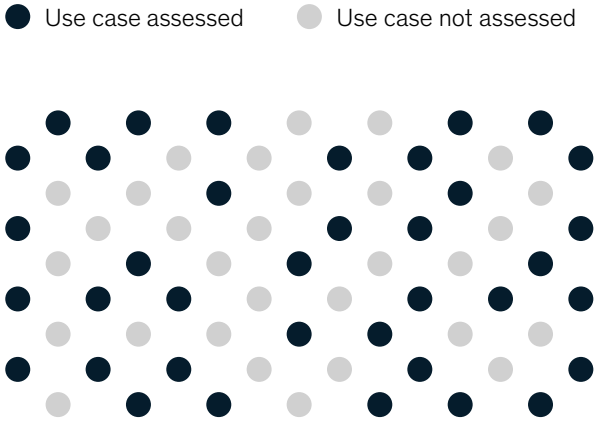
[160] Susan Young Rojahn, "A decade of advances since the Human Genome Project," *MIT Technology Review*, April 12, 2013.

Exhibit 10

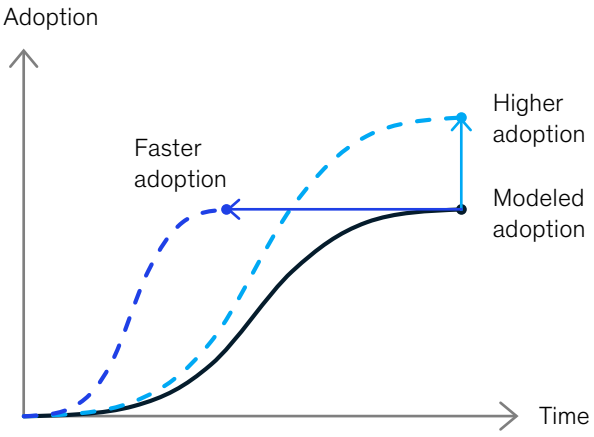
The total economic impact could be larger than the direct impact assessed.

Examples

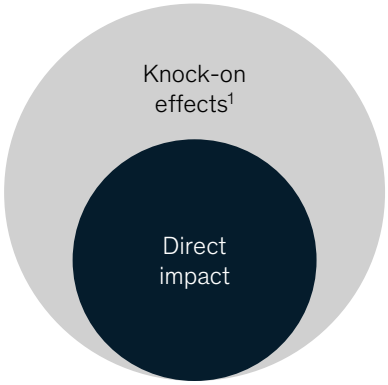
Impact from unassessed use cases today



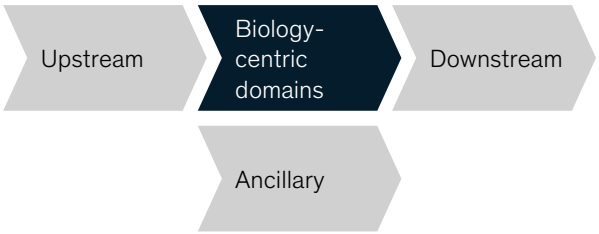
Faster or higher adoption than modeled



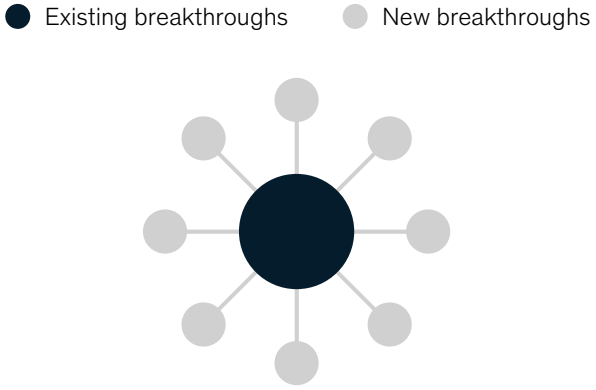
Knock-on economic effects[1]



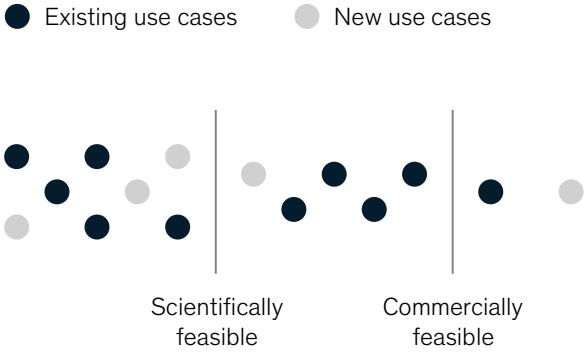
Impacts to upstream, downstream, and ancillary players[2]



Existing scientific breakthroughs spurring new scientific breakthroughs



Future scientific breakthroughs enabling new commercial applications



1. Examples of direct impacts include willingness to pay more for perceived improved health benefits; examples of knock-on effects include reduced agricultural land use from shifting to plant-based proteins.
2. These sectors are not inherently biological but experience indirect impact because they are the upstream, downstream, and ancillary players of the biology-centric domains, including entertainment, finance, insurance, professional services, and travel. In contrast, biology-centric domains are a cluster of sectors where core products or services could be inherently biological, such as agriculture, medical products, and pharmaceuticals.

Source: McKinsey Global Institute analysis

For now, we don't have certainty into the degree to which these potential societal effects will be realized. Nonetheless, based on what we can see already today, we observe that there could be potential for biological implications in the following areas:

— **Sustainable development, environment.** Climate change is one area where biology could play an important role. By 2040 to 2050, the direct applications we sized could reduce annual average man-made GHG emissions by 7 to 9 percent from 2018 levels, or up to eight times the total CO_2 emissions from the global airline industry in 2018.[161] This would come from a variety of applications such as a shift toward new bioroutes for production and alternative proteins. The knock-on effects include alleviating pressure on cropland and reducing deforestation. Adopting bio innovations, such as using more sustainable inputs rather than plastics, could address other environmental challenges such as waste. At the same time, there is also potential for some of these applications to have unintended consequences on species or ecosystems, given the interconnected nature of biological systems (see chapter 6.5 for other biological applications focused on sustainability).

— **Sustainable development, food security.** There is also potential to improve food security and reduce world hunger and malnutrition through agricultural applications. The Bill & Melinda Gates Foundation, for example, suggests that by using improved fertilizer and more productive crops such as genetically engineered varieties, African farmers could theoretically double their yields.[162] New portable DNA sequencing devices developed by Oxford Nanopore Technologies, which first appeared in Africa for Ebola surveillance, can empower farmers on the continent to better fight crop disease—but they remain expensive at $1,000 apiece, and adoption may take off only as the price comes down. Through the Cassava Virus Action Project, the pocket DNA sequencers allow rural farmers in East Africa to receive actionable insights about viruses in real time (compared with the normal three months) for the first time.[163] Reducing the cost and health risk or improving the shelf life of various foods could have broad-reaching implications for global hunger. More effective biopesticides and biofertilizers may lead to more efficient crop production systems and potentially contribute to reducing world hunger.

— **Workforce.** Bio innovations also have workforce implications. Demand for people with expertise in genetics, bioinformatics, biochemistry, bioengineering, machine learning, and data analytics skills will rise as talent starts to drive commercialization. A key question is how to ensure that these skills are available to organizations that can develop beneficial applications.

— **Society.** Finally, there are implications for our societal fabric. Our use cases suggest that biological applications can already have health benefits in the form of longer and more productive life. This comes with broader ramifications. If people live longer and in better health, retirement ages and demand for eldercare may rise even further. The way we work may change. If we are to live longer, could we spend more time in education and start working later? Could we use the additional healthy years of work to develop more specialized skills or enjoy a second career? Finally, are we happier as a population with increased omics insights and the ability to engineer ourselves? Is that necessarily a good thing?

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[161] Total GHG emissions, including from land use, land-use change, and forestry, were 75.9 $GtCO_2e$ in 2018, according to the UN's *Emissions gap report 2019*. All GHG emission figures in this report are expressed using 20-year global warming potential (GWP20) instead of using 100 years to emphasize the shorter-term climate impacts of GHG emission. The global CO_2 emissions of the airline industry were about 0.9 gigatons in 2018, according to the International Civil Aviation Organization. *ICAO global environmental trends—present and future aircraft noise and emissions,* International Civil Aviation Organization working paper number 54, May 7, 2019.

[162] Elizabeth Lopatto, *Can GMOs end hunger in Africa?*, The Verge, February 2015.

[163] *New portable DNA sequencers help East African farmers fight crop disease*, Cassava Virus Action Project, September 15, 2017.

For all this potential, biological applications will not likely be a panacea for all societal ills and challenges. In many ways, the societal effects could occur unevenly, in part driven by level of access to these innovations across socioeconomic groups or nations. And, critically, the risks of biology will need to be addressed and satisfactorily mitigated if biology is to realize its potential.

Science is the starting point—applications need to be commercialized and diffused responsibly to deliver beneficial impact at scale

In addition to addressing the substantial risks of biological advances, many hurdles still need to be overcome if innovations are to reach their full potential and move from the lab to health systems, businesses, industry, and consumers. The path to impact and adoption will take time. Broadly, the path to adoption has three key stages, which bleed into each other into a continuous evolution. The first is the scientific research stage, where an innovation is discovered, developed, and tested before it reaches the critical point of scientific feasibility, defined as achieving experimental or pilot success in a target population. Once the scientific research is complete, commercialization and scaling can theoretically begin. This is the stage at which new products and services are developed and tested. When they are launched into the market—at which point they are commercially feasible—then diffusion among end users can begin.[164] The pace and extent of that diffusion will depend on many factors, including whether new products and services are cost-competitive with current offerings and whether they offer new, superior properties or higher quality. Essentially, new offerings need to be meet demand from end users to diffuse.

For the applications in our library of use cases and for other applications that may emerge in the future to diffuse and deliver beneficial impact at scale, six broad factors are likely to determine whether an application emerges from an idea, and is then adopted by end users and at what pace this journey may proceed. The first—investing in scientific research—is germane in the first stage. Four factors—value propositions, business models, go to market, and operational scalability—are key for the second and third stages, commercialization and diffusion. The sixth relates to risk and mechanisms for governing the use of applications; this is vital in all three stages (Exhibit 11).

[164] We recognize that not all bio innovations will be launched into a traditional "commercial market" including those deployed by the public sector. We use "commercial availability" and "market launch" to refer to the general idea that the bio innovation has passed sufficient testing that it can now be made available to the target population, in which case the diffusion factors apply, for instance, whether the innovation is superior to alternatives.

Exhibit 11

Six factors affect the pace and extent at which bio innovations are adopted.

Stages of adoption and milestones

Not exhaustive

Scientific feasibility
Experimental success in target population

Commercial availability
First commercial offering

Scientific research From ideas to innovation	**Commercialization** From lab to market	**Diffusion** Spread across population
1. Research investments		
Funding. Scientific research requires considerable investment Talent. Maintaining a cadre of highly talented scientists is critical to sustaining the vitality of research Tools. The development of new tools and technologies in biological sciences extends research capabilities Access to data. The emergence of annotated and accessible scientific databases is pivotal to the development of accessible knowledge		
	2. Value proposition	
	Compelling value propositions offered to initial adopters including increased utility such as improved quality or addressing unmet need	Continuous improvement of value proposition including increased utility, meeting unmet need, and cost competitiveness with existing offerings
	3. Business models	
	New business models may be needed to achieve positive margins; companies experiment with customer segmentation, customer acquisition costs, and pricing, for instance	Continuous improvement of business models
	4. Go to market	
	New offering launched to reach the right audience; elements include product positioning and marketing to educate potential customers	Continuous optimization of marketing and sales strategies including marketing mix and sales channels
	5. Operational scalability	
	Ability to scale for initial adoption, including skills, infrastructure, processes, and supply chains	Continuous improvement of ability to scale including skills, infrastructure, processes, and supply chains
6. Risk and mechanisms for governing use		
Science cannot be pursued in a vacuum, but needs to take account of broader benefits and risks	Societal acceptance and initial regulatory go-ahead where applicable	Societal acceptance combined with ongoing regulatory review and approval; includes post-market surveillance and approval to enter new markets

Source: McKinsey Global Institute analysis

Scientific research, funding, tools, talent, and access to data are powerful enabling investments

Today's innovations were once just ideas. In most cases it took years of research and sizable investments to make them scientifically feasible.[165] Although the exact course of scientific research can be difficult to predict, key types of investment increase the likelihood of more advances. They include funding, the development of tools that extend research capabilities, talent to sustain the vitality of research, and access to data to build knowledge and derive insights.

— **Funding.** Scientific research requires considerable investment. For example, the Human Genome Project involved $3 billion in investment. Years ago, science was largely supported through private patronage—the backing of a prominent person or family—church sponsorship, or self-funding. Today, companies, governments, universities, nonprofit organizations, and others around the world make substantial investments in R&D. Since 2000, total global R&D expenditures have nearly tripled, from $676 billion to $2 trillion in current dollars. These funding programs often have systematic evaluation processes, which aim to improve the quality of research, and diverse priorities, which could affect specific fields of science and engineering.

— **Tools.** The development of new tools and technologies in biological sciences has extended research capabilities well beyond genome sequencing. CRISPR represents a major leap forward in the ability to edit genes. Ever-increasing computing power at ever-decreasing cost has underpinned the rapid development of the bioinformatics needed to gain insights from omic technology. And noninvasive imaging techniques such as magnetic resonance imaging (MRI), positron emission tomography (PET), and magnetoencephalography (MEG) have become powerful enablers of biomachine interfaces.[166] Other important advances include the development of noninvasive neural imaging techniques with resolution comparable to that of invasive techniques, as well as the creation of safer and more advanced gene delivery techniques that, in combination with genome editing tools, can create an end-to-end genetic modification system.

  Technological advances in several fields outside biology are also enabling unprecedented quantitative analyses of biological systems. These fields are diverse, including physics, electronics, chemistry, nanotechnology, computer science, and information technology. In most instances, tools and methods developed for specific applications in their respective fields have been adapted for use in probing biological systems. But in many cases, the complexity of biological systems presents new challenges that call for creative solutions and additional innovation. Microfluidic chips for cell culture with up to 100 chambers, using techniques drawn from engineering, chemistry, and physics, have been designed to hold individual cells and all the microscopic plumbing necessary to add any combination of different chemical inputs to those chambers. The chips can be used to test how different inputs might cause stem cells to transform into more specific cells needed for treatments. They could also be used to test how different combinations of antibiotics affect a particular bacterium.

[165] We define scientific feasibility as experimental success in the target population (for instance, in the case of human health, success in humans rather than in mice models). For applications where we could not identify proof of concept in academia or industry, we assessed feasibility using sector-specific analogs and expert interviews that estimate how far away scientific feasibility might be.

[166] MRI is a medical imaging technique using magnetic fields and radio waves to create detailed images of the inside of the body. PET is an imaging test that uses a radioactive drug to reveal the status of tissues and organs. MEG is a noninvasive neuroimaging technique for direct mapping brain activity by recording magnetic fields generated by electrical currents occurring naturally in the neurons of the brain.

— **Talent.** Maintaining a cadre of highly talented scientists is a critical element in sustaining the vitality of research. Doctoral study plays an important role in developing future innovations by training the researchers needed to advance knowledge and explore new research areas. Over time, the number of research doctorates and other graduate degrees awarded in science and engineering shows a strong upward trend. For example, in the United States between 1976 and 2016, the number of recipients of science and engineering doctorates more than doubled, with an average annual growth rate of 2 percent.[167] Between 2013 and 2017, the number of students graduating with a doctorate increased by approximately 8 percent across OECD countries.[168] Policies intended to ensure more equitable access for men and women have contributed to this trend. Despite the importance of doctoral training, the pathway to a scientific career does not begin in undergraduate or postgraduate years; rather, an interest in science is kindled in the early years of formal education. Every educational and developmental stage is a potential point of intervention, and a comprehensive approach to nurturing students' interest in science and engineering must be adopted to address the talent pipeline.

— **Access to data.** The emergence of annotated and accessible scientific databases, such as the Human Genome Project, GenBank, and UniProt, is pivotal to the development of a substantial base of accessible knowledge. So too has been the development of a wealth of information and best practices related to modeling organisms, including *E. coli, C. elegans*, and *Arabidopsis thaliana*; knowledge about, and experience with, cell and tissue culturing; and the building of a substantial base of knowledge related to bioinformatics. Structured scientific databases, whether public or private, could be a critical enabler to identifying population-level trends. When combined with new advances in machine learning, the ability to glean powerful new insights could be significant. Only with such knowledge about the underlying biology—for instance, which genes cause which disease, condition, or even behavior—can we successfully engineer genes and build the infrastructure to scale bio innovations. In addition to enabling more scientific breakthroughs, enhanced access to data could lead to better reproducibility of research results, improved trust in science, and more innovation. These benefits need to be balanced against the costs, including the need to protect privacy and security and prevent malevolent uses. Accordingly, "as open as possible, as closed as necessary" is gradually replacing the "open-by-default" mantra associated with the early days of the open-access movement.[169] However, enhanced access to data poses several outstanding policy challenges, from systems and processes to ensure transparency and foster trust across the research community and wider society to appropriate recognitions and rewards to encourage researchers to share data.

Commercialization and diffusion: Four factors play a role

Once an application is scientifically feasible, other factors will determine the journey from lab to market to wide adoption and diffusion. Do the economics of a particular application work or not? Is the supply chain supported by adequate infrastructure? Is there demand among customers? How fast could the economics improve with new biologically based production methods? The answers to these questions bear on whether companies or governments are prepared to invest in innovation and develop an application to the point where it is commercialized and scaled, and then adopted widely. In this section, we look at the four factors applicable to these second and third stages of the journey from the lab to market. None of them can be achieved as a one-off, but they must constantly be in play to ensure that innovations keep moving along, diffusing more widely into different geographies, and responding as the science, markets, competitive dynamics, and economies continue to evolve.

[167] *2016 doctorate recipients from U.S. universities*, National Science Foundation, March 2018.
[168] *Education at a glance 2019*, Organisation for Economic Co-operation and Development, September 2019.
[169] OECD, *OECD science, technology and innovation outlook: Adapting to technological and societal disruption*, Paris: OECD Publishing, 2018.

— **Value propositions.** However innovative the science is, new applications need to have a compelling value proposition. They must compete with existing products by providing improved utility, for instance through some combination of cost competitiveness, new insights, improved quality, and improved safety, or by offering a novel product that addresses unmet needs. Cost competitiveness may be only one of several dimensions that could make a new product or service enabled by biological advances attractive to potential users, but it is an important one. Many potential buyers of biology-based products are in industries with typically low margins, such as agriculture and energy. Moreover, once a method of production has existed for decades, years of efficiency gains have already been captured. Bio innovation, like other novel technologies, will need to overcome this head start to attract market demand even if applications have actual, theoretical, or eventual cost and quality advantages. Diffusion can take significant time, and costs can remain high for a considerable period. The first efforts to grow cultured proteins for space exploration began around the turn of the millennium.[170] It took until 2013 for humans to taste the first lab-grown hamburger, which was produced at a cost of more than $300,000.[171] Since then, however, production costs have fallen dramatically with the development of processes that enable industrial-scale production. Cultured meat could hit supermarket shelves in the next ten years.

  In the case of biofuels, the price of oil is a critical determinant of whether they are viable, and although they may offer environmental advantages, biofuels have struggled to compete. Interest in aviation biofuels has been rising; many companies are active in this area. However, these fuels have not come close to replacing traditional fossil-fuel-based aviation fuel because of their production cost, which was between $1 and $2.50 per liter in 2019, compared with $0.30 to $0.60 per liter for traditional aviation fuel, according to the International Energy Agency.[172] However, pricing in externalities (for example, the societal costs of net carbon emissions) could change the cost calculus—a significant driver of whether a technology is viable for investment and adoption.[173]

— **Business models.** To best ensure that frontier biological technologies offer customers value, new business models may be needed. New business models may include new ways of monetizing data or establishing platform-based business models (see chapter 5 for further discussion). Platform models are proliferating in sectors such as agriculture.

— **Go to market.** Once an innovative product or service has a compelling value proposition, an effective way of delivering it to end users is then needed. Key decisions must be made about, for instance, pricing, sales, and marketing. Arguably even more than in the case of traditional products and services, in the fast-moving innovative biological field, the imperative to continually refine and adapt strategy may be even stronger to respond to new competitors as they emerge and adapt as target markets become more competitive. In some cases, there has been considerable excitement about biology-based innovations—at-home genetic testing is an example. It is important for companies to avoid overhyping products (that may rest on incomplete or flawed science) only because they see early customer demand, lest the market collapses as the underlying assumptions are shown to be shaky. Some DTC testing companies in the past claimed to find associations

[170] Neil Stephens, Alexandra E. Sexton, and Clemens Driessen, "Making sense of making meat: Key moments on the first 20 years of tissue engineering muscle to make food," *Frontiers in Sustainable Food Systems*, July 10, 2019; and Muhammad Sajid Arshad et al., "Tissue engineering approaches to develop cultured meat from cells: A mini review," *Cogent Food & Agriculture*, 2017, Volume 3, Issue 1.

[171] Pallab Ghosh, "World's first lab-grown burger is eaten in London," BBC, August 5, 2013; and Alastair Jamieson and Alan Boyle, "'Intense flavor': The $330,000 burger that was built in a lab hits the spot," NCB News, August 5, 2013.

[172] *Production cost and break-even crude oil price for SAFs compared with fossil jet kerosene, 2019*, International Energy Agency, March 2020.

[173] Examples of policies addressing externalities include cap-and-trade schemes in the case of combating climate change. In such schemes, fuel suppliers must buy pollution permits (also called allowances) to cover their remaining carbon pollution. Cap-and-trade schemes create incentives to purchase cleaner products such as biofuels because the more fuel suppliers reduce their carbon pollution, the fewer allowances they need to buy.

between genes and capabilities such as emotional control, memory, and athletic ability, but the science behind such associations is weak.[174]

— **Operational scalability.** Considerable effort is required to scale operations from individual laboratory experiments to industrial scale in order to serve a growing customer base. Several components of operational scalability, including infrastructure, processes, supply chain, and talent, have been and will continue to be crucial to commercializing and diffusing bio innovations.

Infrastructure, processes, and supply chain need to be addressed to scale up. Infrastructure includes, for instance, the large-scale fermentation technology that was developed by pharmaceuticals and chemicals manufacturers to create large quantities of biological drugs and materials over the past half-century. This infrastructure should enable much more rapid scaling of next-generation fermentation-based technologies. The global market for fermented chemicals was estimated at $85 billion in 2017.[175] A great deal of infrastructure is already in place, but more will be needed. It may seem obvious, but the components of modern healthcare delivery—hospitals, labs, outpatient centers, pharmacies, and so on—are crucial for the dissemination of medical innovations. For instance, CAR T-cell therapy is extremely complex to administer and requires a hospital stay. The storage and movement of most gene and cell therapy products occur at ultra-low or cryogenic temperatures.[176] CAR T-cells are now being administered to growing number of patients in hospitals and treatment centers, meaning sufficient infrastructure for manufacturing and delivering these cells is necessary.[177]

In addition, sufficient appropriate talent must be in place to drive commercialization of bio innovation. Just one example where the talent pool in healthcare is already under strain is genetic counselors, who help patients and the public understand and interpret the results of genetic tests and the trade-offs of subsequent decisions.[178] These professionals are critical for the spread and successful adoption of genetic sequencing technologies. However, there are too few of them at a time when the amount of genetic information being generated is rising rapidly. More counselors are needed to keep pace with that explosion in data to ensure their responsible use in a consumer setting where there is no medical supervision.[179] Broadly, this requires more education and training about the technologies and their applications.

Risk and mechanisms for governing use are relevant in all three stages

Given the profound and unique risks accompanying bio innovation, mechanisms governing use, including broad acceptance by society and regulation, are key both in the first research stage and when the science commercializes and diffuses. Even if an application is scientifically feasible and well developed and the economics are favorable, end users and other stakeholders—whether individuals, businesses, or healthcare systems—must want to use innovative biology-based products and services, and in many cases that means accepting some risk. Our research finds that about 70 percent of the total potential impact could hinge on consumer, societal, and regulatory acceptance, based on an analysis of areas where regulations exist today in major economies.[180]

[174] Emily Chang, "In China, DNA tests on kids ID genetic gifts, careers," CNN, August 3, 2009.
[175] Fermented product sales based on 2017–2018 data from IHS Markit.
[176] Chad Presher and Meridith Hyres, *The impact of gene and cell therapy on the supply chain*, Clinical Trials Arena, July 20, 2018.
[177] Jacob Bell, *Car-T ups challenges in pharma supply chain*, Biopharma Dive, April 23, 2018.
[178] Jennifer M. Hoskovec et al., "Projecting the supply and demand for certified genetic counselors: A workforce study," *Journal of Genetic Counseling*, February 2018, Volume 27, Issue 1.
[179] Stephanie Miceli, *At-home DNA tests still need the 'human touch,' say panelists at genomics roundtable workshop*, The National Academies of Sciences, Engineering, and Medicine, November 13, 2019.
[180] We examined existing regulations and their applicability to sized applications. Applications were also considered at stake if they relate to highly sensitive topics in academic circles, such as embryo editing and bioweapons. Our analysis is as of September 2019.

The way technologies are seen and spoken about in the media, and by members of the public at large, will help determine the degree of societal acceptance, the reaction of regulators and legislators, and the behavior of companies trying to market or react to biological applications. For example, users must have a degree of trust to enable sequencing and analyzing a person's genome, editing their children's genes, or placing a biomachine interface device in a person's brain. Major successes could capture the public imagination, and that might drive increased investment and a flow of talent to support further innovation. A biological disaster would likely have the opposite effect, causing a public backlash that could dampen investment, elicit a tough regulatory response, and hinder adoption.

There is no uniformity in societal acceptance of bio innovations. Many of them, including genetic engineering of crops and, even more so, human beings, are perceived differently by different people in different cultures; what seems like an acceptable trade-off for some between scientific progress and risks may not be acceptable to others. Hence, bio innovations will need to gain societal acceptance if they are to be commercialized and prove successful in the marketplace. Citizens have considerable sway over regulators, and their views vary enormously, leading to a variety of regulatory approaches in different countries. It is already evident that innovation is geographically uneven, partly reflecting different regulatory approaches.

The case of Golden Rice is illustrative.[181] In 1982, scientists started developing vitamin A–fortified rice to combat vitamin A deficiency in poor regions. Although the first strain of the genetically engineered grain was produced in 2000, a general lack of support from the public and attempts to block regulatory approval by anti–genetic engineering activists have delayed commercialization for nearly two decades. In December 2019, the Philippines became the first country with many people suffering from vitamin A deficiency to approve Golden Rice. [182] The Philippine Department of Agriculture Bureau of Plant Industry said that it found Golden Rice to be as safe as conventional rice.[183]

The pace and extent of adoption of bio innovations vary significantly depending on the application

Applications will journey from the lab to commercialization and diffusion at different speeds; indeed, they already are doing so. Historical analogs suggest that the pace and extent of adoption at scale are highly variable. These adoption curves span domains and geographies to give a sense of the approximate average adoption timelines and spread in different circumstances (Exhibit 12).

We used these analogs in our estimate of the timing of adoption as well as the shape of adoption curves (timing agnostic) for biological applications. We estimated low and high levels of peak adoption and the time it may take to reach peak adoption; we also modeled the adoption curves for each application. This simplification enables us to arrive at a feasible estimate of potential economic impact; we recognize that adoption levels may continue to increase with shifting product features and value propositions, changing cost structures of these applications and substitutes, and customer demographics.

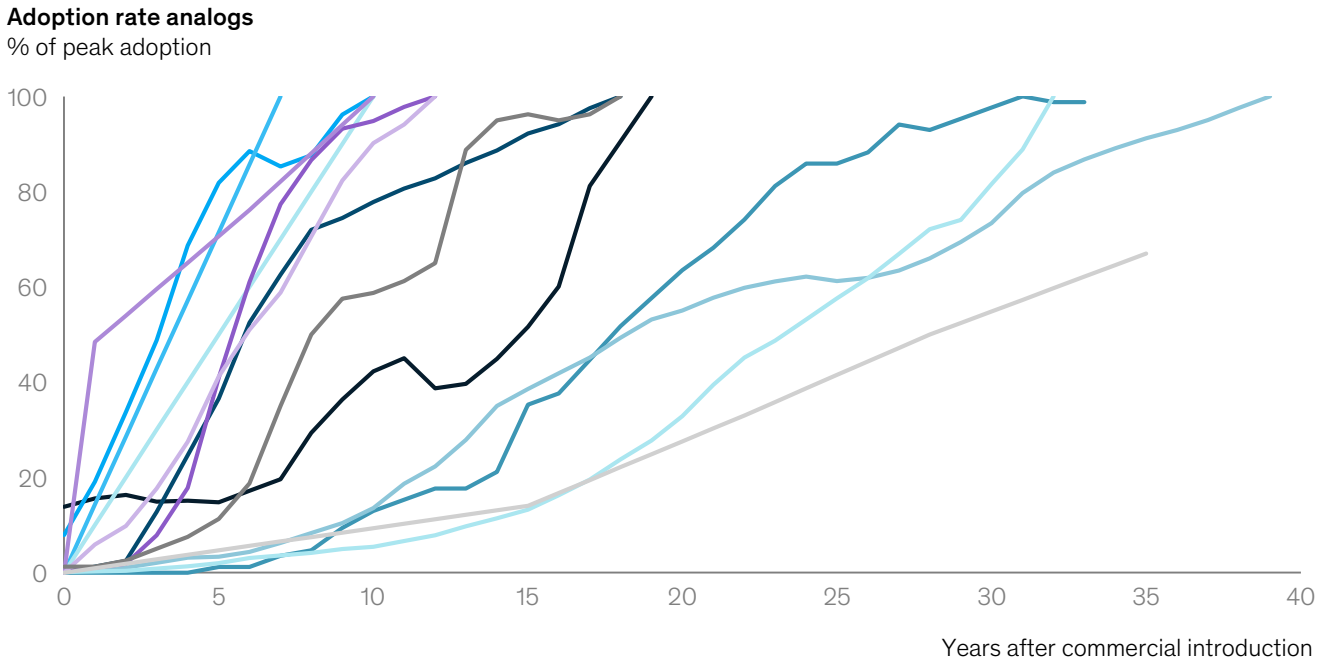
[181] Jesse Hirsch, "Golden Rice: A brief timeline of the world's most controversial grain," *Modern Farmer*, August 27, 2013. Also see J. Madeleine Nash, "This rice could save a million kids a year," *Time*, July 31, 2000.

[182] Prior to approval in Philippines, Golden Rice was registered as safe in Australia, Canada, New Zealand, and the United States, all countries with few vitamin A deficiency problems. See Michael Le Page, "GM golden rice gets landmark safety approval in the Philippines," *New Scientist*, December 31, 2019. This is based on World Health Organization data on the prevalence of vitamin-A deficiency in pregnant women and preschool-age children from 1995 to 2005. See WHO, *Global prevalence of vitamin A deficiency in populations at risk 1995–2005*, WHO Global Database on Vitamin A Deficiency, 2009.

[183] *Philippines approves nutritionally-enhanced GMO Golden Rice for human consumption*, Genetic Literacy Project, December 18, 2019.

Exhibit 12

Analogs suggest adoption rates for new technologies will vary by domain.



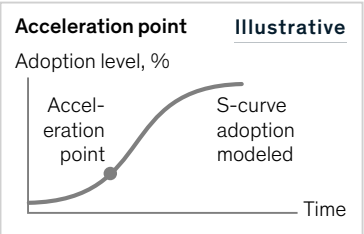
Source: McKinsey Global Institute analysis

The pace and extent of adoption vary among applications within domains and among them (Exhibit 13). Some applications, such as using new bioroutes for drug manufacturing, are already showing strong signs of progress toward commercialization and adoption. Others, such as plant-based proteins, have recently become commercially viable; adoption is at an early stage but could increase rapidly over the coming decade. Still others, such as using genetically engineered plants to sequester CO_2, show promise in the lab, but commercial viability and adoption by farmers or other buyers are likely to be further out; to commercialize, they need to demonstrate that beyond their carbon-capturing ability, they can compete on cost and yield with plants that are already established among other factors that need to be addressed.

Exhibit 13

Among applications assessed, adoption timing varies.

Example use cases Not exhaustive	Estimated time horizon of acceleration point of use cases across domains The acceleration point is when adoption starts to experience rapid growth[1] **Existing** Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
Human health and performance[2]	Carrier screening Noninvasive prenatal testing	CAR T-cell therapies for liquid tumors Liquid biopsy	Gene drives to reduce vector-borne diseases CAR T-cell therapies for solid tumors	Transplantable organs produced from stem cells Embryo editing for medical purposes (eg, via CRISPR)
Agriculture, aquaculture, and food[3]	Marker-assisted breeding (crops and animals used for food) Genetic tracing of food origin, safety, and authenticity (eg, allergens, species, pathogens)	Plant-based proteins Crop microbiome diagnostics and probiotic treatments	Cultured meat Genetically engineered animals—faster growth	Genetically engineered crops—faster growth through enhanced photosynthesis
Consumer products and services[4]	DTC genetic testing—ancestry	Personalized meal services based on genetic and microbiome profile DTC genetic testing—personal insights about health and lifestyle	Biosensors for monitoring of personal health, nutrition, and fitness based on omics data	Gene therapy—skin aging
Materials, chemicals, and energy[5]	New bioroutes for drug manufacturing (eg, peptides)	Novel materials—biopesticides/biofertilizers (eg, RNAi pesticides) Improved existing fermentation processes—food and feed ingredients (eg, amino acids, organic acids)	Novel materials—biopolymers (eg, PLA, PET)	Biosolar cells and biobatteries
Other applications	DNA sequencing for forensics		Biosequestration of CO_2 Bioremediation for pollution	



1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.
2. Applications in the human health and performance domain include innovations to reduce disease burden at the individual and population levels, anti-aging treatments that extend life span, reproductive health (eg, carrier screening) applications, and innovations in drug development and manufacturing. See chapter 6.1 for the full list of applications that we sized in this domain.
3. Applications in the agriculture, aquaculture, and food domain include applications related to plants and animals for food purposes, food production, food transportation, and food storage. See chapter 6.2 for the full list of applications that we sized in this domain.
4. Applications in the consumer products and services domain include direct-to-consumer genetic testing, beauty and personal care, wellness (eg, fitness), and pets. We categorize wellness, nutrition, and fitness under consumer rather than health, because they do not directly alleviate the global disease burden or are elective or for adult enhancement, such as hair loss or cosmetics. While some of these applications could have indirect impact on the disease burden, such as fitness wearables, they are not direct treatments or therapies. See chapter 6.3 for the full list of applications that we sized in this domain.
5. Applications in the materials, chemicals, and energy domain include innovations related to production of materials (eg, improved fermentation process, new bio-routes, or novel materials), and energy production and storage. See chapter 6.4 for the full list of applications that we sized in this domain.

Source: McKinsey Global Institute analysis

Science is propelling innovation, but even when the applications of that science could have benefits, there is no guarantee that innovation will be commercialized and adopted. Many barriers stand in the way, and the journey from the lab to adoption may be long and arduous. Nevertheless, the Bio Revolution appears to have reached an acceleration point, with about 400 applications in a wide range of domains scientifically conceivable. Most of these are already scientifically feasible and many are moving toward commercialization, promising impact even in the relatively near term of the next ten to 20 years. Beyond that point, the impact is expected to radiate outward to almost every sector, transforming society in important ways and making our economies and human activity more sustainable.

Earth from Apollo 17
© Stockbyte/Getty Images

5. Implications for stakeholders

Given the breadth of change that likely lies ahead, innovators, businesses, governments, and individuals need to become literate in biological science in order to understand the fundamental shifts under way and seize the large potential benefits, but in a way that ensures that innovation is safe for citizens and society.

The many uncertainties about how and when the numerous applications may spread through economies and societies might suggest that taking a wait-and-see approach could make sense. However, it could be far more beneficial to get ahead of the curve—or at least keep pace with it—and start calibrating a portfolio of clear-headed responses now. The imperative is to attempt to strike the right balance between fostering innovation and capturing the large potential benefits while at the same time giving serious attention to the many risks involved. The choices made today and in the years ahead will influence not only the path of bio innovation but also the size of its benefits for stakeholders and, beyond them, for economies, society, and the planet.

Innovators have a key role to play in ensuring sufficient oversight of innovation as it develops

The scientists and researchers pioneering biological breakthroughs in academic, public, and private labs, and the developers and innovators who turn feasible science into commercially viable products, are in the vanguard of bio innovation. They are the ones who need to push the envelope on the science—to innovate—but also are the ones who should identify risks associated with their work and raise them for broader discussion. Scientists govern their own research processes. Peer review is a powerful internal governing mechanism to ensure that research is accurate and well grounded. But scientists cannot operate in a vacuum; to an extent, they need to take into account the views of society in the research they propagate. The scientific community must play a consistent and effective oversight role, and it has a track record of doing so. As far back as 1975, prominent scientists, lawyers, and medical professionals gathered at the Asilomar Conference in California to draw up voluntary guidelines to ensure the safety of recombinant DNA technology.[184]

Debate about the right balance between scientific endeavor and discovery and societal interests is ongoing. The case of a highly dangerous genetically engineered form of bird flu is a good example. In 2011, two separate teams in the United States wanted to publish the results of the research project, but the National Science Advisory Board for Biosecurity argued that the results in full would provide a road map for spreading the virus for hostile reasons. Eventually, the study results were released in full, but the episode highlighted difficult issues about how to handle "dual-use" bio innovations intended for the public good but arguably too easily misused.[185] Scientists in other fields, such as nuclear physics and AI, are grappling with some analogous issues, and there could be room for cross-disciplinary collaboration.

[184] Recombinant DNA molecules are formed by combining genetic material from multiple sources to create sequences not found in the genome (molecular cloning, for instance). See Paul Berg et al., "Summary statement of the Asilomar Conference on recombinant DNA molecules," *Proceedings of the National Academy of Sciences*, June 1975, Volume 72, Number 6.

[185] Martin Enserink, "Scientists brace for media storm around controversial flu studies," *Science*, November 23, 2011; Donald G. McNeil Jr., "Bird flu paper is published after debate," *New York Times*, June 21, 2012; and David B. Resnik, "H5N1 avian flu research and the ethics of knowledge," *The Hastings Center Report*, March–April 2013, Volume 43, Issue 2.

Businesses should consider how to take advantage of bio innovation, including adapting strategies

The potential value of biological applications over the next two decades makes a compelling argument for business adoption. The scientific innovations in turn could drive a proliferation of new products and services, markets, and business models. Just as happened with digital, biological applications will bring a cohort of new competitors eager to take on incumbents. Applications in every domain have spillover effects on other sectors. This means businesses face potentially far-reaching shifts in value chains and profit pools.

Spillover effects to upstream, downstream, and adjacent sectors

Applications in one domain will often have impact and knock-on effects on a range of sectors. Take healthcare as an example. The large amount of data generated through omics and related technologies will need to be collected, stored, analyzed, and shared, suggesting a need for even more capacity in these areas and greater integration between information technologies such as AI, the management of big data, and the Internet of Things; all of this will involve IT players. Electronics industries will need to manufacture cutting-edge devices like sequencers, spectrograph machines, biosensors, and wearables. The lines are blurring between healthcare and consumer sectors, with many innovations in the former being adopted and adapted by the latter.

In the case of applications in agriculture, aquaculture, and food, there will be spillover into food retailing, for instance. Numerous fast-food chains have announced deals with plant-based meat-substitute producers to offer vegetarian and vegan versions of popular menu items. Beyond Meats and Impossible Foods have worked with chains such as Burger King, Dunkin', and Kentucky Fried Chicken over the past two years. Cultured meat may reach the high-end market over the next five years through specialty restaurants—settings where consumers are less price-sensitive.[186] If bio innovations mean that products have longer shelf lives and that plants can be grown in different climates, restaurants and supermarkets may be able to offer wider choice to consumers. Logistics and transportation players may need to adjust to produce being kept fresh for longer even without being refrigerated, and to increased demand for alternative proteins. For example, Sysco, a leading global food-service-distribution company, launched the Sysco Simply platform in 2018. It is designed to enable customers to accommodate growing consumer demand for varied dietary and lifestyle choices, including plant-based meat substitutes.[187] Crop insurance may be affected by new traits that result from genetically engineered production systems. For instance, premiums charged in drought programs could be reduced due to new drought-resistant traits in crops. Product liability insurance taken out by retailers and food chains may also be affected by advances in tracing food safety and origin. Clear Labs, for example, says its automated testing platform based on next-generation sequencing can eliminate foodborne illnesses and product recalls.[188]

Applications in consumer markets could affect insurers. If new consumer products and services that guide behavior based on biological information lead to improved nutrition, fitness, and health outcomes, insurance providers could pay their customers to use them (similar to paying those insured for quitting smoking, losing weight, or taking other actions to improve their health). Workplace wellness programs could also adopt these innovations, enabling employers to lower premiums for those who comply.

[186] Zafer Bashi, Ryan McCullough, Liane Ong, and Miguel Ramirez, *Alternative proteins: The race for market share is on*, McKinsey & Company, August 2019.
[187] *Introducing Sysco Simply: A platform dedicated to health and well-being food solutions*, Sysco, November 1, 2018.
[188] Katy Askew, "'We can effectively eliminate recalls': Clear Labs eyes $100bn food safety opportunity," FoodNavigator, November 2, 2018.

Innovations in materials, chemicals, and energy could potentially spill over into numerous sectors that use these products as inputs. In the case of materials, the consumer packaged goods industry could look very different; for example, the materials used in many consumer products could shift from plastic to bio-based plastic packaging as customers increasingly demand packaging and products that are more sustainable. In apparel, fashion, and luxury, new supply chains could emerge as production shifts to less natural-resource-heavy production technologies that consumers may demand. For example, consumers may want to purchase goods that are not made with leather for animal welfare and environmental reasons. In the case of fuels, the production of new, more sustainable biofuels may require new underlying technologies in, for instance, engine design.[189] Biofuels have the potential to alter the aerospace, travel, and logistics industries if aviation biofuel is scaled and commercialized, and becomes more price competitive. If biodiesel is widely adopted for trucks and transportation, demand from the logistics industry for petroleum may decrease. That said, thus far, biofuels have struggled to be cost-competitive with traditional fuels.

Biomachine interfaces also have numerous potential uses across sectors. Transportation and hospitality players may use neuroergonomics to improve travel comfort and safety.[190] Neuroergonomic headsets that are able to provide information on the stress levels of consumers may be useful in research on customer experience and may inform the development of new products that will improve comfort. In finance, futuristic biomachine interfaces that augment human capabilities for quantitative analysis may greatly benefit high-volume traders and financial analysts. If advanced surgically implanted brain-computer interfaces are developed and adopted, it may well be that insurance policies will need to adjust their pricing and offerings to consumers—bearing in mind that these devices may reduce or raise risk. The defense industry is both upstream and downstream for other sectors. What happens in the military will draw on innovations in other sectors from healthcare to materials, but also influence and drive innovation in those sectors. Military medicine has already driven change in civilian healthcare settings, two examples being trauma care and treatment of PTSD.[191]

Shifting value chains

Biological applications could lead to changes in value chains, although these shifts will not often be easy nor quick. In agriculture, rising demand for alternative proteins could disrupt the value chain.[192] Prior to distribution of meat (and seafood), animals are bred, fed, slaughtered (fished), and processed. In contrast, the value chain for cultured meat and seafood is significantly compressed, involving only live-tissue sampling and cultivation of cells into meat, processes often performed by the same company (Exhibit 14). Moreover, new players in alternative proteins are aiming to be both biotech startups and aspirational consumer brands. This "lab-to-table" approach consolidates profit pools. In addition, suppliers of inputs for production of alternative proteins might scale or emerge. For example, some companies focus on supplying the hardware, cell lines, and small molecules that are needed to grow meat in the lab.[193] An equally transformative shift in value chains could happen in materials as plant-based materials spread.

[189] Biodiesel made from plant material could hold promise as a more sustainable alternative to diesel from fossil fuels. However, the molecular makeup of these fuels means they boil at different temperatures than petrodiesel, and therefore they can only be used in specially designed engines. German scientists have found a way to transform plant-based chemicals into a biodiesel that meets the boiling characteristics required by the European Committee for Standardization. See Edd Gent, "Biofuel could work in regular diesel engines," *Scientific American*, June 20, 2017.

[190] Neuroergonomics is a research field that investigates the human brain functions—perceptual, cognitive, and motor functions—in relation to behavioral performance in natural environments and everyday settings.

[191] See, for instance, K. V. Brown et al., "Modern military surgery," *Journal of Bone and Joint Surgery*, British volume, April 1, 2012, Volume 94-B, Number 4; and John B. Holcomb, "Major scientific lessons learned in the trauma field over the last two decades," *PLoS Medicine*, July 2017, Volume 14, Issue 8.

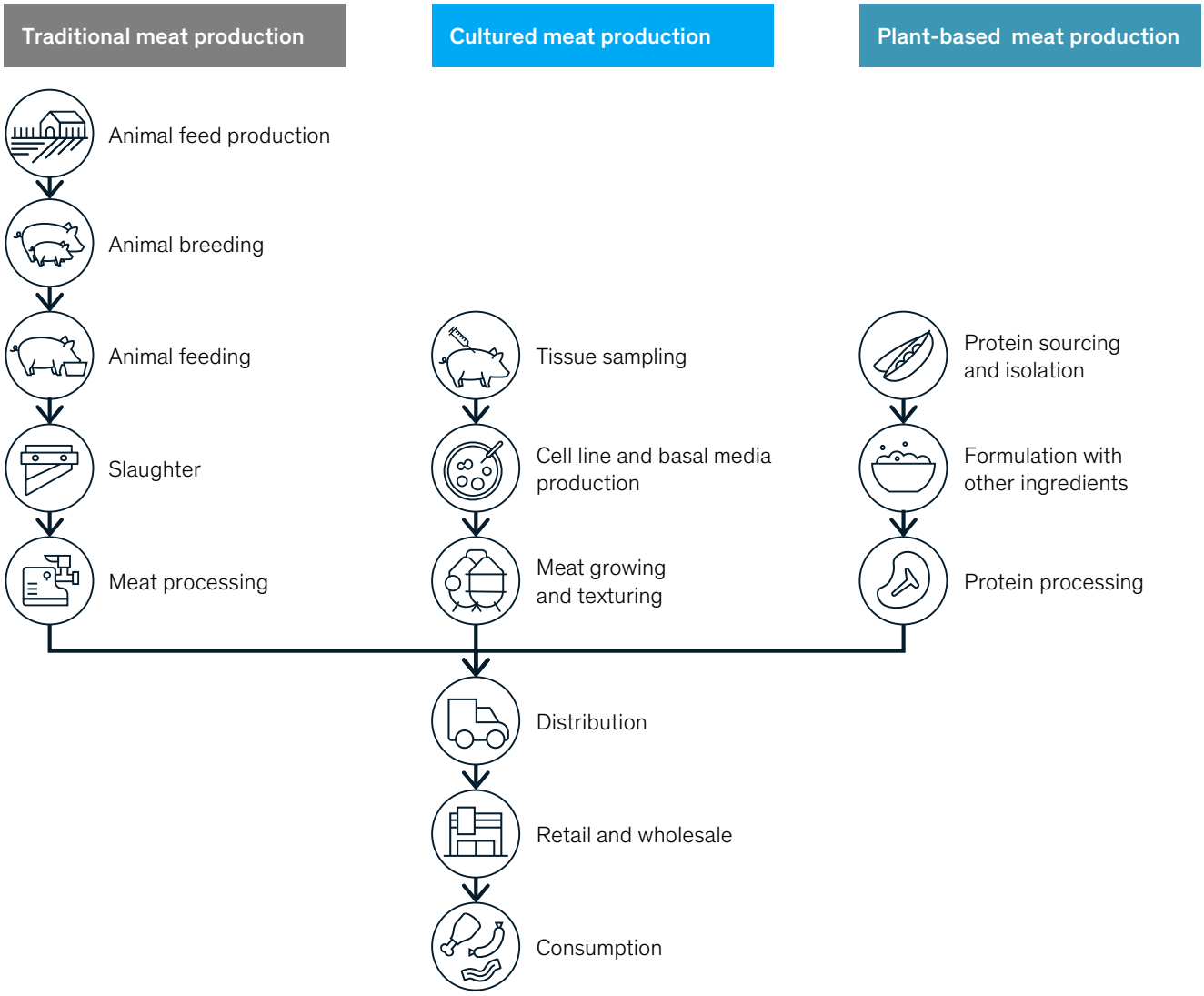
[192] *Our meatless future: How the $1.8T global meat market gets disrupted*, CB Insights, November 13, 2019.

[193] Jonathan Shieber, *Lab-grown meat could be on store shelves by 2022, thanks to Future Meat Technologies*, TechCrunch, October 10, 2019.

Exhibit 14

The meat value chain is shifting.

Traditional meat production vs cultured meat and plant-based meat production



Source: McKinsey Global Institute analysis

The structure of healthcare systems could also be altered. New diagnostics and treatments are changing the way patient care is delivered, with implications for providers, including hospitals, clinics, and long-term-care facilities. First, there could be a shift in where care is delivered. A proliferation of point-of-care diagnostics such as gene sequencing for cystic fibrosis could decentralize care from the most advanced and specialized centers for diagnostics and treatments to local and accessible facilities for care. Personalized medicine could spread and be delivered in secondary centers. As biological applications shift from treating disease to curing or preventing it, there could be less acute care and more preventive primary care.

Second, the way biological data are used could change. Data that make it easier to identify conditions and treatments earlier could enable a move from an inpatient to an outpatient setting or perhaps even to the home. Players that aggregate data and create centralized data repositories could appear. They could also share data with pharmaceutical companies to improve R&D. Some DTC testing startups are using R&D collaborations to move up the value chain and tap into the profit pools of the pharmaceutical industry. One DTC testing company that is moving in this direction is Viome, which has raised $25 million to conduct about 15

clinical research trials with a view to developing its own treatments.[194] Another example is AOBiome's role in the development of microbiome drugs; the company launched a Phase 2 clinical trial for the treatment of hypertension and a Phase 2B trial for its treatment for acne vulgaris.[195] The use of cell and gene therapies often relies on companion diagnostics that identify the right patients. The diagnostics value chain is still inefficient due to factors such as potentially high costs and slow adoption by physicians.[196] These factors can hinder access to new therapies.[197] It could be that pharmaceutical companies move to develop, manufacture, or provide access to diagnostics to boost the utilization of therapies.

Companies will need to adapt their business strategies

Companies have a critical role to play in accelerating adoption by working with the scientific community, focusing on scientific advances and technologies that are likely to have the most impact, investing in them, partnering with innovative startups, reinventing their own organizations where appropriate, and managing risks. There are a number of elements to consider.

Adopt a portfolio-based approach toward investing in bio innovation given the uncertainty and varied timing of adoption

Given the varied timing with which applications are moving from lab to market, a portfolio-based approach—that is, looking at use cases that are likely to be adopted over different time horizons—may make sense. In the immediate future, focusing on applications where the science is already advanced, where there is a compelling economic case, and where they can be adopted at scale would seem advisable. In parallel, businesses could pick a small number of potentially high-impact applications where the science is not fully established, and then work with researchers and specialized startups to push innovation forward through experimentation.

Master the confluence of disciplines in bio innovation with the right mix of talent and collaborations

New collaborations are sprouting up as companies move to capture the opportunities of bio innovation, spurred by the cross-disciplinary nature of advances. As technologies rapidly evolve, and biotech and AI converge, both larger incumbents and smaller, science-based startups could struggle on their own to drive R&D and navigate commercialization. "Barbell-shaped" ecosystems characterized by cross-sector networks in which many small, science-based companies are balanced by a few large incumbents are emerging and driving the commercialization of new biological technologies.

Small, science-based startups currently at the forefront of innovation are pushing the boundaries of what is possible and what some incumbents might consider too risky to do themselves. This is leading to a growing range of collaborations between new players embracing the high risk and high rewards of science-based opportunities and incumbents ready to invest in the unique biological capabilities of these newcomers. For example, to capture the cost effectiveness and higher precision of the new gene-editing technology CRISPR, established players in agriculture and pharma are among those setting up R&D collaborations with CRISPR players, such as Caribou Biosciences, CRISPR Therapeutics, and Pairwise. Some incumbents, hedging their bets, are choosing to partner with multiple—and, at times, competing—startups.

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194 Jonathan Shieber, *As researchers pursue links between bacteria and human health, startups stand to benefit*, TechCrunch, April 17, 2019.

195 *AOBiome partners with iCarbonX and secures $30 million investment for drug development*, AOBiome Therapeutics, January 5, 2017.

196 Chris Lo, "Precision medicine: What barriers remain?," Pharmaceutical Technology, March 2, 2020; and Geoffrey S. Ginsburg and Kathryn A. Phillips, "Precision medicine: From science to value," *Health Affairs*, May 2018, Volume 37, Issue 5.

197 Turna Ray, *Report says many precision drugs will launch in coming years but unclear if they will reach patients*, Genome Web, October 22, 2019.

From full-blown acquisitions to more agile and short-term collaborations, large incumbents are testing different partnership approaches with smaller, science-based startups. In some cases, large incumbents with extensive customer networks are well positioned to test and launch the new products produced by smaller players lacking an existing customer base. For instance, players such as Novozymes and Inari are striking up partnerships with established seed producers of various sizes that have long-standing relationships with farmers and growers to introduce omics-driven innovations. In other cases, opportunities emerge for deeper collaboration and investment to leverage the larger partner's commercial expertise and navigate regulation and commercial-approval processes better. In the area of brain-computer interfaces, Facebook spent between $500 million and $1 billion in 2019 to acquire CTRL-labs, a tech startup that translates neural signals from muscles as inputs in software.[198] These varying relationships offer benefits for both players and are pivotal to the commercial success of many of the new biological technologies. As the boundaries of traditional biological industries and other sectors blur, understanding the growing role of barbell-shaped ecosystems in driving R&D and commercial opportunities will become a greater source of competitive advantage for both incumbents and new science-based startups.

In addition to collaborations, businesses will also need to develop the right mix of talents with various biological capabilities. New specialty skills in fields such as genomics, molecular biology, biochemistry, and neuroscience will increasingly be in high demand. Indeed, the merging of digital skills with biological skills will be a potent combination.

Platform-based business models in biology can seize cross-sector opportunities, reduce marginal costs, and drive combinatorial innovation by leveraging growing biological data

Many of the world's largest corporations favor platform-based business models—a centralized technology and data platform licensed to other players or for proprietary use—that enable them to seize cross-sector opportunities, reduce marginal costs, and mine large-scale data sources to drive combinatorial innovation. Such platforms are particularly relevant for R&D-intensive sectors. Now companies with growing sources of biological data, like their digital predecessors, are integrating automation and machine learning to accelerate the pace and variety of scientific discoveries. These platform-based models enable businesses to deliver a diverse set of advantages that were unthinkable even a few years ago.

To understand the nature of opportunities offered by biological platforms opportunities, consider agriculture. Companies selling farming equipment, seeds, or agricultural chemicals are now developing or partnering to create software-based platforms that act as farm management systems.[199] NRGene has a cloud-based breeding platform that can analyze genomic data to inform scientists and breeders which sequences offer beneficial traits.[200] The rise of sophisticated and extensive computer modeling with genetic and microbiome insights can supplement traditionally slow, sequential experimentation and open the door for these new platforms to compete.

Beyond agriculture, platform players looking for speedier growth are expanding the accessibility and use of their platforms, allowing other companies—including potential competitors—to build products or services on top of their databases. For example, Ginkgo Bioworks recently announced the Ferment Consortium, giving spin-off companies full access to its genome-mining platform for cell programming.[201]

198 Kurt Wagner, "Facebook to buy startup for controlling computers with your mind," Bloomberg, September 24, 2019; and Nick Statt, *Facebook acquires neural interface startup CTRL-Labs for its mind-reading wristband*, The Verge, September 23, 2019.

199 Geoffrey Carr, "Factory fresh," *Economist Technology Quarterly: The Future of Agriculture*, June 2016.

200 BASF and NRGene, *BASF and NRGene collaborate to accelerate crop breeding*, October 29, 2019.

201 "Ginkgo Bioworks announces the Ferment Consortium, a $350 million investment vehicle to disrupt established markets with new synthetic biology companies," PR Newswire, October 10, 2019.

Gaining momentum and armed with "data flywheels" in which each new piece of data makes collecting the next piece easier, platforms are becoming a growing source of competitive advantage in the Bio Revolution. Incumbents will need to understand how these platforms are evolving to identify where the most attractive opportunities lie. In the future, incumbents might choose to take advantage of others' platforms or consider creating their own platforms to rapidly experiment and learn at scale.

Seize the opportunities for more personalized and precise offerings emerging from the growth of biological data

Advanced personalization and precision, powered by a growing amount of biological data—including genetic makeup and microbiome composition—is set to transform and, in many cases, deepen relationships among customers, the products they use, and the companies that make the products. While most of the hype around the Bio Revolution is around new technologies such as CRISPR used to manipulate biological processes, our research shows that applying insights derived from analyzing biological data accounts for more than 50 percent of the economic potential over the next ten years. Businesses today are already planning on how to monetize the exabytes of genetic data collected each year. Some DNA- and microbiome-testing companies are using proprietary databases to launch personalized nutrition products and services as add-ons. New offerings include, for instance, subscription-based meal plans and dietary supplements that claim to be tailored to customers based on DNA- and microbiome-testing results. These new players, increasingly in competition with consumer-goods, services, and marketing companies, will provide unique experiences and points of differentiation.

In addition to personalization, growing biological data banks are increasingly providing new opportunities for precision products and services as well in industries such as agriculture and medicine. With an emerging understanding of the role of the microbiome, precision agriculture is set to drive innovative farming solutions that improve operational efficiency and economic output. For example, Trace Genomics interprets health and disease-risk indicators by profiling the soil microbiome. These insights can help growers in choosing tailored seeds, nutrients, and other inputs, adding to the tool kit for precision agriculture that also includes satellite imaging and geospatial analysis.

Incumbents will be able to maintain or capture new value only if they look at the entire ecosystems of their products and services and begin to understand how to use biologically derived insights to outperform their competitors. This may come through personalized, seamless experiences—such as precision medicine delivering the right drug for the right therapy at the right time—or through precision products and services driving operational efficiencies.

Innovate with new revenue models that can help accelerate diffusion

In consumer markets, companies are actively looking at new ways to monetize data. Despite declining costs, companies currently offering one-off DTC genetic testing are likely recording a loss on each test due to the high cost of acquiring customers because of the need to engage in extensive marketing. However, companies engaged in DTC testing are increasingly finding other ways to monetize the biological data they gather. Most DTC companies sell individuals' genetic data to pharmaceutical companies for drug R&D. As noted, many DTC genetic testing providers also sell data to incumbents in consumer markets that are increasingly interested in mining this data to add a new layer of personalization. Another approach is helping to generate sales leads from recommendations based on test results. For instance, ingredients on the shopping lists generated by DNAfit's MealPlanner or Habit's app can be purchased directly from online retailers mySupermarket.co.uk and Amazon Fresh, respectively.

Subscription-based offerings to generate revenue are becoming more common in personal insights and in personalized products and services based on genome and microbiome profiles.[202] These subscriptions provide companies with recurring, predictable revenues and help to lock in consumers. As whole genome sequencing gains in prominence and lends itself to subscriptions, many players are trying to settle on pricing and a marketing strategy.[203] This is not straightforward, because whole genome sequencing involves complex information and many variants. This makes it difficult for consumers to distill insights and understand the value proposition compared with more narrowly focused single nucleotide polymorphism analyses.[204]

Civil society, governments, and policy makers need to inform themselves about biological advances to provide thoughtful guidance

Given the breadth of the potential changes from biological advances that we have outlined in this report, it will be incumbent on all leaders to inform themselves and keep abreast of the latest scientific and commercial developments. The twin goals will be to capture the potential rewards that biology can offer and, at the same time, to understand and address the risks posed by this ongoing wave of innovation. Choices made today and in the years ahead will influence not only the path of adoption, but also the size of the benefits for stakeholders and, beyond them, for economies, societies, and the planet.

The profound risks that this wave raises have inevitably prompted discussion about the capacity of existing professional and regulatory mechanisms to govern these activities. The novelty of these applications also provides an opportunity to reflect more generally on the principles governing these innovations and demand a considered response and, potentially, new approaches.

Governments can set a strategic direction for biology-based innovation that encourages and enables the scientific community and business leaders. In 2008, the US National Institutes of Health, National Science Foundation, and Department of Energy asked the National Research Council's Board on Life Sciences to set up a committee to look at how the United States was positioned on biological research and how to build on it.[205] China and the United Kingdom have also invested in biology-based innovation as a priority, publishing formal strategies.[206] The leader of China's Basic Research Department said the country was seeking to position itself as a global leader in synthetic biology, motivated by a need to address the country's public health, nutrition, and resource needs.

Managing risks and mechanisms that govern the use of biological applications—including regulation, which often reflects societal opinion—will be vital. Many bio innovations—including genetic engineering of crops and, even more so, of human beings—are viewed with concern, discomfort, or sometimes outright hostility.

In the next ten years, more than 50 percent of the total potential impact of the Bio Revolution could hinge on consumer, societal, and regulatory acceptance, based on an analysis of areas where regulations exist today in major economies.[207] This rises to more than about 70 percent in the next ten to 20 years. Some higher-risk applications, for example adult gene therapy, will likely be more regulated and thus adopted later, whereas other applications such as microbial

[202] Companies offer a complete genome sequence at certain cost, and then a subscription fee to unlock insights over time as the science evolves to reveal more about how to interpret the genome.
[203] Whole genome sequencing is a method for analyzing the entire DNA sequence of an organism's genome.
[204] "Now you can sequence your whole genome for just $200," *Wired*, November 19, 2018.
[205] *A New Biology for the 21st Century: Ensuring the United States Leads the Coming Biology Revolution*, National Research Council, Washington, DC: The National Academies Press, 2009.
[206] *Emerging policy issues in synthetic biology*, Organisation for Economic Co-operation and Development, 2014; and *Positioning Synthetic Biology to Meet the Challenges of the 21st Century, Summary Report of a Six Academies Symposium Series*, Washington, DC: The National Academies Press, 2013.
[207] Analysis includes examination of existing regulations in different countries and their applicability to sized applications. Applications are also considered at stake if they are related to highly sensitive topics in academic circles, such as embryo editing or bioweapons. Analysis of existing regulations as of September 2019.

skin-care products that are less risky and therefore relatively less regulated may have an easier and faster path to adoption.

Given the level of risk and uncertainty, regulation is seldom straightforward and is likely to be highly dependent on the context. Different societies with different value systems will accept different levels of uncertainty and risk under different circumstances. One example is genetically engineered crops.[208] Public perception differs markedly from country to country and can change over time. One cross-cultural survey showed that Italian and Japanese consumers rate GMO-free as a more important characteristic than US consumers do.[209] Another survey found that only 11.9 percent of Chinese consumers have a positive view of genetically engineered food.[210]

In addition to public perception, regulation of genetically engineered crops also differs among geographies. Leaders in the adoption of genetically engineered crops include, in order of most land used for their production, the United States, Brazil, Argentina, and Canada.[211] In the EU, 19 out of 28 member states have voted to partially or fully ban the cultivation and sale of genetically engineered food products.[212] In Africa, genetically engineered food products are legal in just a few countries. Both China and the EU have mandated the labeling of traditionally genetically engineered food products since 1997 and 2002, respectively.[213] In January 2020, China issued "biosafety" certificates for the commercialization of domestic crops of GM soybean and two types of corn after a ten-year halt.[214] The United States followed suit in 2018, requiring genetically engineered food products to be labeled "bioengineered."[215]

For the second wave of genetically engineered crops whose genomes have been altered with gene-editing technologies like CRISPR, the US FDA has declared that it will not regulate the plants as long as the editing does not lead to foreign DNA in the plant.[216] The US Department of Agriculture views gene editing as the equivalent of traditional breeding of plants—a genetically engineered plant without foreign genetic material is indistinguishable from plants developed using traditional breeding methods. In contrast, a landmark European court ruling made gene-edited crops subject to the same stringent regulations as other GMOs.[217] At the time of writing, the stance of regulators elsewhere remained to be seen.[218]

A second example of highly variable approaches to governing the use of particular biological applications is preimplantation genetic testing (PGT) or diagnosis (PGD), a technique to help identify genetic defects within embryos prior to preimplantation.[219] As of late 2019, the United

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208 Starting in the 1990s, genetic engineering emerged commercially to improve the yields and productivity of plants beyond traditional breeding. There are two waves of innovations in genetic engineering organisms. In one, genetically modified (GM) crops involve transgenic modifications (using genes from non-plant organisms such as bacteria). The next began with the arrival of genetic editing technologies (for instance, CRISPR) which are now enabling highly specific and efficient cisgenic changes (using genes from sexually compatible plants) and intragenic changes (changing gene combinations and regulatory sequencing belonging to the recipient plant).

209 Shahla Wunderlich and Kelsey A. Gatto, "Consumer perception of genetically modified organisms and sources of information," *Advances in Nutrition*, November 2015, Volume 6, Issue 6.

210 Kai Cui and Sharon P. Shoemaker, "Public perception of genetically-modified (GM) food: A nationwide Chinese consumer study," *npj Science of Food*, Number 10, 2018.

211 *Biotech crop highlights in 2017*, International Service for the Acquisition of Agri-biotech Applications, Pocket K Number 16, October 2018, updated December 2019.

212 *Several European countries move to rule out GMOs*, European Green Capital, European Commission.

213 *Genetically modified organisms*, European Commission; and Alice Yuen-Ting Wong and Albert Wai-Kit Chan, "Genetically modified foods in China and the United States: A primer of regulation and intellectual property protection," *Food Science and Human Wellness*, September 2016, Volume 5, Issue 3.

214 Zhou Tailai and Denise Jia, "China issues biosafety certificates to domestic GM soybean, corn varieties," *Caixin Global*, January 23, 2020.

215 Cheryl Hogue, "US requires labelling of GMO foods as 'bioengineered,'" *Chemical & Engineering News*, December 27, 2018.

216 CRISPR-based editing in plants does not introduce foreign DNA. To mutate a gene of interest in a plant, scientists first grow protoplasts—plant cells lacking a cell wall. They then introduce preassembled CRISPR complexes, including a tailor-made stretch of guide RNA and the nuclease Cas9, to the protoplasts. The complex homes in on the target gene and cuts the DNA at a locus specified by the guide RNA. Protoplasts are then grown in clumps that are regenerated into a mature, genetically modified plant.

217 Ewen Callaway, "CRISPR plants now subject to tough GM laws in European Union," *Nature*, July 25, 2018.

218 Jon Cohen, "To feed its 1.4 billion, China bets big on genome editing of crops," *Science*, July 29, 2019.

219 Preimplantation genetic testing is genetic testing of an embryo prior to embryo transfer (to a uterus) during IVF. This can be done to test for single gene disorders such as cystic fibrosis (preimplantation genetic diagnosis, or PGD) or overall chromosomal abnormalities such as Down syndrome caused by an extra chromosome (preimplantation genetic screening, or PGS).

States had few restrictions. The American Society for Reproductive Medicine largely leaves individual clinics and parents to decide what is permissible.[220] The procedure can be used in the United States for any condition for which genetic testing is available. Although it is primarily used to detect serious heritable disorders, such as cystic fibrosis, it can also be used for more controversial purposes, such as sex selection. In contrast, the Human Fertilisation & Embryology Authority in the United Kingdom tightly regulates the procedure, permits its use for medical purposes only, and maintains a detailed list of disorders for which it is permitted.[221] In China, the procedure is permitted only for detection of serious diseases—not for sex selection—and its use has taken off since the government explicitly made this form of screening a priority.[222]

Differences in approach are also evident with the sharing of genomic data. The United States treats genomic data in the same way as health data under the Health Insurance Portability and Accountability Act of 1996. The EU tightly guards omics data with special provisions under its General Data Protection Regulation. China has rules governing sharing of omics data and imposes restrictions on data leaving the country, reflecting a broad stance in favor of controlling the flow of genomic data out of China. At the same time, there is concern about China acquiring data from outside the country for use by its scientists and companies.[223]

Regulation to an extent reflects public opinion. It also reflects government views of the public interest, including economic competitiveness. Lighter-touch regulation may deliver—or be seen to deliver—competitive advantage compared with a more restrictive approach. A regulatory "race" could put pressure on the more cautious to adopt more laissez-faire approaches, potentially exposing them to increased risks. Each jurisdiction will need to grapple with the interaction of regulation and innovation.

While value systems and regulations vary from country to country, national responses to bio innovations will be limited, because biology doesn't respect borders—as we are experiencing firsthand with COVID-19. A coordinated international response would not only be more beneficial for managing risk, but would also help countries propel collaborative innovation.

Individuals and consumers may be pivotal to the adoption path of biological advances

Individuals, as consumers, play a large role in assessing the value of innovations, influencing public discourse and shaping adoption. Individuals must understand the various trade-offs of new applications that generate new insights, become knowledgeable about the scientific advances and their risks, and proactively engage in public dialogue and policy making.

Consumers may not always be fully aware of the potential impact of biological applications on their privacy, for instance. DTC testing is one example, as discussed in chapter 3. Many individuals were unaware that their data were being shared by third parties. Individuals also need to be aware that the science behind a consumer application of biology may not always be solid. Again in the case of DTC testing, one analysis found that 40 percent of variants in a variety of genes reported in DTC raw data were false positives; retesting in a clinical laboratory showed that the variant was not actually present.[224] Some variants designated as being "increased risk" in DTC raw data or by a third-party interpretation service were classified as benign by clinical laboratories.[225] It may be that individuals should push for more

[220] M. J. Bayefsky, "Comparative preimplantation genetic diagnosis policy in Europe and the USA and its implications for reproductive tourism," *Reproductive Biomedicine & Society Online*, December 2016, Volume 3.
[221] Ibid.
[222] In 2017, estimates suggested that preimplantation genetic testing (PGT) was performed more often and growing five times faster in China than in the United States. The popularity of this procedure owes much to the fact that diseases with a genetic source carry a heavy stigma in China. See David Cyranoski, "China's embrace of embryo selection raises thorny questions," *Nature*, August 16, 2017.
[223] David J. Lynch, "Biotechnology: The US-China dispute over genetic data," *Financial Times*, July 31, 2017.
[224] Stephany Tandy-Connor et al., "False-positive results released by direct-to-consumer genetic tests highlight the importance of clinical confirmation testing for appropriate patient care," *Genetics in Medicine*, March 2018, Volume 20.
[225] Ibid.

information before taking a test, and it is possible that DTC companies should provide genetic counseling. France and Germany ban DTC genetic testing altogether due to requirements that call for medical or some other type of informed supervision and genetic counseling.

Beyond ensuring that they protect their privacy and inform themselves to avoid misselling, individuals can have a powerful voice in determining the stance of regulators, as we have seen in the case of genetically engineered crops and, even more so, the prospect of genetic engineering of human beings.

The rapid advances in biology in recent years amount to a powerful new wave of innovation that is expected to transform business and society. Healthcare is already seeing growing adoption of biological applications, and many other sectors are also being affected. The traditional journey of protein from farm to plate may be replaced with a path that starts in a lab. Novel materials produced with a reduced carbon footprint can conserve the natural resources we currently use in manufacturing. There are massive opportunities for businesses to create more value for customers and shareholders. For all the excitement about bio innovation, the path ahead is fraught with risks and serious ethical issues. Scientists and regulators will need to work together to ensure that these innovations do not cross ethical boundaries and to assuage public concerns even while giving science the room to explore new directions. Biology has no borders any more than climate change does; the case for cooperation as well as competition is compelling if this wave of innovation is to proceed—and proceed safely—for the benefit of all.

Scientist lifting sprout from petri dish with tweezers
© Adam Gault/OJO Images/Getty Images

6. Applying bio innovation

As noted earlier in this report, we group bio innovations into four arenas—biomolecules, biosystems, biomachine interfaces, and biocomputing. Here we dig deeper into the library of use cases and discuss applications of evolving biological science in key domains, from healthcare and agriculture to consumer products, energy, and the environment. Applications have different adoption horizons and present a wide range of opportunities, risks, and challenges. The use cases we spotlight are by no means exhaustive; these applications merely constitute the visible pipeline that we were able to examine in depth. Many other applications will surface in coming years. Overall, the breadth of uses and potential uses is a testament to just how powerful and wide-ranging the potential for biological sciences could be for business, the economy, and society more broadly. In the following sections of chapter 6, we discuss a wide range of use cases that could have direct impact in the next ten to 20 years, but also applications that have potential impact further out. We start by exploring biomolecules and biosystems innovations across domains, and then explore innovations in biomachine interfaces and biocomputing.

Preparation of an immunotherapy treatment
© Garo/Science Source Images

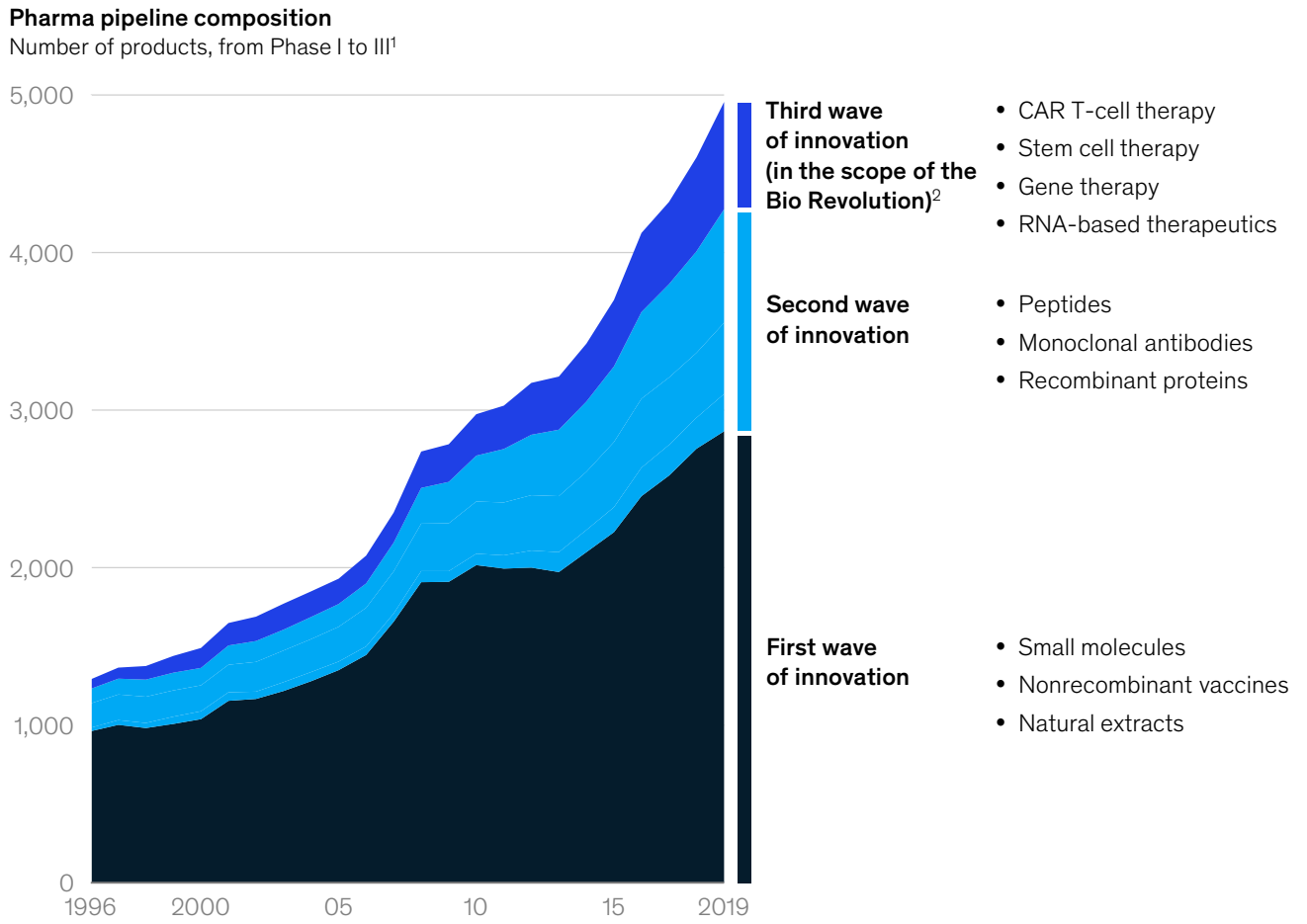
6.1. Human health and performance

The range of technologies being used in healthcare today is taking off, creating a steep innovation curve (Exhibit 15). Conventional therapies, including small molecules, nonrecombinant vaccines, and natural extracts constituted a first wave of pharmaceutical innovation. A second wave included protein-based biologics such as peptides and monoclonal antibodies.[226] Today, a third wave is under way that includes new approaches such as cell, gene, and RNA therapies. In this section, we discuss a broad range of biomolecules and biosystems innovations to improve human health and performance. There are also advances in biomachine interfaces that improve human health and performance, as discussed in chapter 6.6.

Exhibit 15

A new wave of innovation in healthcare is developing.

Not exhaustive



1. Innovative drugs only, excluding reformulations and biosimilars; snapshot as of June each year with missing phases not approximated; phase based on most progressed indication.
2. Third wave of innovation includes many innovative therapeutics enabled by the Bio Revolution in improving human health. However, examples are not exhaustive and do not include applications of the Bio Revolution in other domains such as agriculture, consumer, etc.

Source: Evaluate 2019; McKinsey Global Institute analysis

[226] We consider these out of scope for this research, as they are part of previous waves of pharmaceutical innovation. As a group, peptides (short chains of amino acids), monoclonal antibodies (made from immune cells), and recombinant proteins are frequently called "biologics." Monoclonal antibodies are made by identical immune cells that are all clones of a unique parent cell.

The pace of adoption will vary (Exhibit 16). Adoption of the full range of gene therapies could be relatively slow unless costs come down because of competition or new financing models. Overall, gene therapies for monogenic diseases are likely to be adopted earlier than those for polygenic diseases, which are more complex. Even among polygenic diseases, the path to adoption varies. CAR T-cell therapy for certain cancers is already showing signs of commercial viability and enthusiastic adoption. By contrast, research into understanding the underlying pathogeneses of neurodegenerative diseases is still at a very early stage, and effective treatments have yet to be discovered.[227]

Exhibit 16

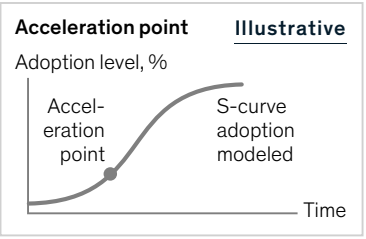
For applications in human health and performance, timing of adoption varies.

Example use cases

Not exhaustive

Estimated time horizon of acceleration point of use cases in human health and performance
The acceleration point is when adoption starts to experience rapid growth[1]

Existing Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
Omics-enhanced drug research and development	Tissues derived from stem cells (eg, hair follicles)	Gene drives to reduce vector-borne diseases	Omics to study and decelerate molecular aging processes
Carrier screening	Liquid biopsy	CAR T-cell therapies for solid tumors	Transplantable organs produced from stem cells
Noninvasive prenatal testing	Mitochondrial transfer	Cell-based and gene therapies to reduce rejection risk of organ transplant	Omics-based screening, diagnosis, and treatment of neurodegenerative diseases (eg, Alzheimer's disease)
Preimplantation genetic testing on embryos for genetic disorders	CAR T-cell therapies for liquid tumors	Omics-based screening, diagnosis, and treatment for infectious diseases and select polygenic diseases (eg, metabolic, cardiovascular, immune disorders)	Guided care using real-time omics
Tissue repair using acellular biomaterials (eg, dural repair patch)	Gene therapies for monogenic diseases		Embryo editing for medical purposes (eg, via CRISPR)
Pharmacogenomics			Embryo screening for nonmedical traits (eg, hair color)
			Embryo editing for nonmedical traits (eg, via CRISPR)



1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.

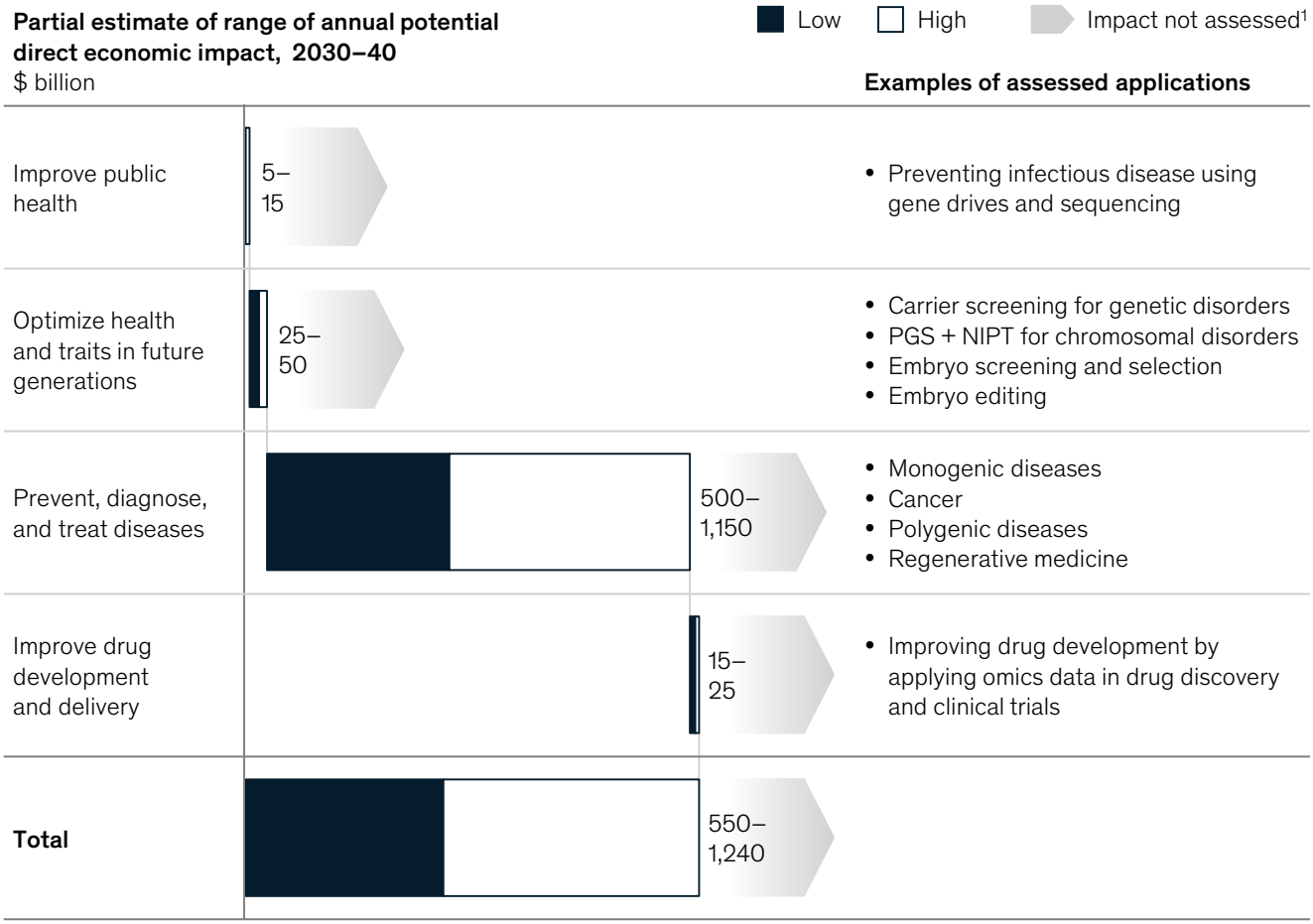
Source: McKinsey Global Institute analysis

[227] Lasse Pihlstrøm, Sarah Wiethoff, and Henry Houlden, "Genetics of neurodegenerative diseases: An overview," *Handbook of Clinical Neurology*, 2017, Volume 145; and Gina Kolata, "An Alzheimer's treatment fails: 'We don't have anything now,'" *New York Times*, February 10, 2020.

In the next ten to 20 years, we estimate that the use of biomolecules and biosystems innovations in healthcare could potentially have annual direct impact of $500 billion to $1.2 trillion globally, which is 33 percent of the total direct impact from our library of around 400 use cases. This impact comes from improvements in human health and performance, mostly measured as a reduction in the global burden of disease translated into workforce productivity (Exhibit 17). In terms of disability-adjusted life years, this equates to between 1 and 3 percent of the total global burden of disease.[228]

Exhibit 17

Annual impact of $0.5 trillion to $1.2 trillion in human health and performance could be created in the next ten to 20 years.


Partial estimate of range of annual potential direct economic impact, 2030–40
$ billion
Low
High
Impact not assessed[1]
Examples of assessed applications
Improve public health
5–15
• Preventing infectious disease using gene drives and sequencing
Optimize health and traits in future generations
25–50
• Carrier screening for genetic disorders
• PGS + NIPT for chromosomal disorders
• Embryo screening and selection
• Embryo editing
Prevent, diagnose, and treat diseases
500–1,150
• Monogenic diseases
• Cancer
• Polygenic diseases
• Regenerative medicine
Improve drug development and delivery
15–25
• Improving drug development by applying omics data in drug discovery and clinical trials
Total
550–1,240

1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.
Source: McKinsey Global Institute analysis

[228] Disability-adjusted life years is a metric developed in the 1990s to measure health and life expectancy across countries. It measures the number of years lost to ill health, disability, or early death.

Much of the impact in the short term will likely come from applications that deliver personalization and precision, because relevant technologies are already relatively mature. Precision medicine in stem cell therapies, for instance, has been developing since the 1980s; today, tailoring of treatment is spreading.[229] Another enabling capability relevant in healthcare—and one likely to have impact over time—is accelerating research (for instance, libraries that identify which genes cause which diseases).

Biological applications in healthcare could potentially affect every disease. A great deal of research is under way not only in genomics, which is most advanced, but in other omics such as epigenomics and proteomics in a broad-based search for new ways to prevent, diagnose, and treat disease and mitigate the health impact of aging. As scientists gain ever more detailed understanding of the molecular pathways of a disease, one can easily imagine a future in which the full range of omics is used in all clinical areas. A new era of regenerative medicine and novel approaches to aging is arriving rapidly. The sections that follow focus on four areas: public health; optimizing health and traits in future generations; the prevention, diagnosis, and treatment of diseases and aging-related damage; and improving the development and delivery of drugs.

Omics could have a substantial positive impact on public health through the prevention of the spread of infectious diseases

Infectious diseases account for 20 percent of the global disease burden.[230] In this section, we cover public health measures that reduce their spread.

Gene drives to reduce vector-borne diseases

An estimated 700,000 deaths globally every year are the result of vector-borne infectious diseases.[231] Until recently, controlling these infectious diseases by altering the genomes of the entire population of the vectors was considered difficult because the vectors reproduce in the wild and lose any genetic alteration within a few generations. However, with the advent of CRISPR, gene drives with close to 100 percent probability of transmission are within reach. This would offer a permanent solution to preventing most vector-borne diseases, including malaria, dengue fever, schistosomiasis, and Lyme disease. Work has already been carried out to genetically engineer mosquitoes so that they can fend off parasites that cause malaria in humans, but until 2014, researchers hadn't found a way to ensure that the pertinent genes would spread rapidly through the wild population, which gene drives can do. Making conservative assumptions about adoption, the estimated annual direct impact from gene drives could be between roughly $5 billion and $10 billion in the next ten to 20 years, reflecting the potential of these approaches to address a large portion of today's global disease burden. For now, the promise of gene drives has yet to materialize, and considerable risks must be managed if the drives are to be deployed responsibly, as discussed in chapter 3 of this report.[232] The National Academy of Sciences has warned that "considerable gaps in knowledge" remain about gene drives' ecological and evolutionary effects.[233]

[229] Andy Coughlan, "Stem cell timeline: The history of a medical sensation," *New Scientist*, January 30, 2014.
[230] IHME Global Disease Burden 2017, Global Health Data Exchange.
[231] A vector is an organism that does not cause a disease but spreads the infection from one host to another; one example is the female anopheles mosquito, which transmits malaria. See *Vector-borne diseases*, World Health Organization.
[232] James P. Collins, "Gene drives in our future: Challenges of and opportunities for using a self-sustaining technology in pest and vector management," *BMC Proceedings*, July 2018, Volume 12, Supplement 8; and Jackson Champer, Anna Buchman, and Omar S. Akbari, "Cheating evolution: Engineering gene drives to manipulate the fate of wild populations," *Nature Reviews Genetics*, February 2016, Volume 17.
[233] *Report in brief: Gene drives on the horizon: Advancing science, navigating uncertainty, and aligning research with public values*, National Academies of Sciences, Engineering, and Medicine, 2016.

DNA sequencing of pathogens to detect outbreaks

Genomics-related diagnostics can help to isolate pathogens and mutated strains quickly, which is highly valuable in the case of pandemics or the rapid emergence of new diseases, particularly outbreaks of hospital-acquired infections.[234] Since the first bacterial genomic sequencing in 1995, inexpensive, ultra-high-throughput DNA sequencing technology has developed and turned what had been an expensive public health exercise into a routine one.[235] Apart from epidemiological investigation, these diagnostics can also identify the antimicrobial susceptibility of the pathogens and therefore help clinicians to administer the right antimicrobials quickly. We estimated that the direct annual economic impact of pathogen sequencing may range from about $2 billion to $4 billion.

Many companies, including Illumina, Thermo Fisher, and BGI Genomics already offer DNA sequencing for pathogens. Further, DNA biosensors that can detect pathogenic DNA in the environment—in food, water, and air—have been available since 2002 but have not yet been widely adopted.[236]

At the time of publication, the world is struggling to contain a new coronavirus that causes COVID-19. The outbreak serves to emphasize the global threat of diseases. It also, however, illustrates the advances that have been made in the scientific ability to understand and deconstruct such pathogens. Chinese scientists sequenced the virus's genome and made it available on the internet on January 10, weeks after the first report of pneumonia from an unknown virus was reported in Wuhan. Labs all over the world started working on developing diagnostics, treatments, and vaccines.[237]

Optimizing health and traits in future generations is possible but fraught with controversy

The ultimate prevention strategy for most genetic disorders is to detect and avert them before individuals are born. There is tremendous potential here, but also significant ethical concerns. The total direct annual impact of all omic and molecular technologies used in screening and intervention could range from roughly $25 billion to $50 billion in the next ten to 20 years.

There are three stages to the reproductive journey during which omics-based screening and intervention techniques play an important role: preconception planning, conception, and pregnancy. In the first area, carrier screening is a genetic test performed on individuals thinking of starting a family to determine if they are carriers of recessive diseases. In the past, carrier screening was available for only a small number of diseases, including Tay-Sachs and cystic fibrosis.

In the second stage—conception—prospective parents who are identified as carriers of certain genetic diseases can opt to use advanced reproductive technologies such as in vitro fertilization (IVF) with embryo screening and selection or, in the distant future, even embryo editing to prevent disorders.[238] Currently IVF can be used to screen for conditions like Down syndrome or cystic fibrosis (a genetic disorder), but could be used in the future for selection based on the relative risk of developing a polygenic condition such as diabetes.[239] It is also

[234] Carrie Arnold, "Outbreak breakthrough: Using whole-genome sequencing to control hospital infection," *Environmental Health Perspectives*, November 2015, Volume 123, Number 11.

[235] Carol A. Gilchrist et al., "Whole-genome sequencing in outbreak analysis," *Clinical Microbiology Reviews*,July 2015, Volume 28, Issue 3.

[236] V. Kavita, "DNA biosensors—a review," *Journal of Bioengineering & Biomedical Science*, April 2017, Volume 7, Issue 2; and Krista M. Ruppert, Richard J. Kline, and Md Saydur Rahman, "Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: A systematic review in methods, monitoring, and applications of global eDNA," *Global Ecology and Conservation*, January 2019, Volume 17.

[237] Antonio Regalado, "Biologists rush to re-create the China coronavirus from its DNA code," *MIT Technology Review*, February 15, 2020.

[238] In vitro fertilization (IVF) is a type of assisted reproduction technology in which an egg is fertilized by sperm outside the body.

[239] Julianna LeMieux, "Polygenic risk scores and genomic prediction: Q&A with Stephen Hsu," *Genetic Engineering & Biotechnology News*, April 1, 2019; and Lynn B. Davis et al., "A cost-benefit analysis of preimplantation genetic diagnosis for carrier couples of cystic fibrosis," *Fertility and Sterility*, April 2010, Volume 93, Issue 6.

now scientifically feasible—but highly controversial—to edit embryos, for instance by using CRISPR. For example, in November 2018, a Chinese scientist made headlines by claiming to have edited human embryos to protect against HIV.[240] He was prosecuted by the Chinese government in 2019 for "illegal medical practices" and sentenced to three years in prison.[241] Other potential nonmedical uses of these technologies—for instance, to influence traits such as hair texture—could push into even more ethically challenging territory.

In the third phase are pregnancy, omics-based noninvasive prenatal testing.[242] Such testing largely diagnoses chromosomal disorders such as Down syndrome from the genetic material of unborn babies in the maternal blood, but could be used in the future to diagnose monogenic disorders.

Prevention, diagnosis, and treatment of diseases and aging-related damage will likely have the most economic impact

The largest potential direct economic impact in healthcare is likely to come from preventing, diagnosing, and treating diseases, according to our analysis. That impact could total between $500 billion and $1.2 trillion a year over the next ten to 20 years, spread across multiple disease areas (Exhibit 18). The majority of the potential impact comes from the prevention, diagnosis, and treatment of cancer, infectious diseases, and aging-related damage to health.[243] Many uncertainties surround the development of technology and the price of innovative new medicines and treatments, and therefore access to them for patients.

Personalized medicine may become a reality in all aspects of disease management. The risk of diseases linked to specific genes can now be predicted by testing the genomics of individuals. Clinical diagnostic tests to segment diseases have been developed based on omics, one example being HER2 protein testing for breast cancer, conducted in the tumor directly.[244] New treatments are being developed, some of which have been approved.[245] Microbiomics—the study of microbes living in the gut, skin, and other areas of the body—also can be of diagnostic and therapeutic value.[246] Numerous startups, including Kallyope and Dermbiont, are researching applications of microbiomics in the cutaneous, gastrointestinal, and reproductive tracts.[247]

[240] Jing-ru Li et al., "Experiments that led to the first gene-edited babies: The ethical failings and the urgent need for better governance," *Journal of Zhejiang University–Science B*, January 2019, Volume 20, Issue 1.

[241] Dennis Normile, "Chinese scientist who produced genetically altered babies sentenced to 3 years in jail," *Science*, December 30, 2019.

[242] Noninvasive prenatal test (NIPT), also known as noninvasive prenatal screening or NIPS, is a noninvasive method for determining the risk that a fetus will be born with certain genetic disorders, primarily used for chromosomal disorders such as Down syndrome by analyzing small cell-free fetal DNA fragments circulating in a pregnant woman's blood.

[243] The World Health Organization estimates that noncommunicable diseases—namely cardiovascular disease, cancer, respiratory diseases, and diabetes mellitus—cause 40 million deaths a year, or 70 percent of all global deaths, and that 17 million people die before they reach the age of 70. See Margaret Chan, *Ten years in public health 2007–2017*, World Health Organization, 2017.

[244] Breast cancers with a HER2 gene amplification or HER2 protein overexpression tend to grow faster, spread farther, and recur more often than breast cancers that are HER2-negative. Treatments specifically for HER2-positive breast cancer are available today. See *HER2 status*, Breastcancer.org.

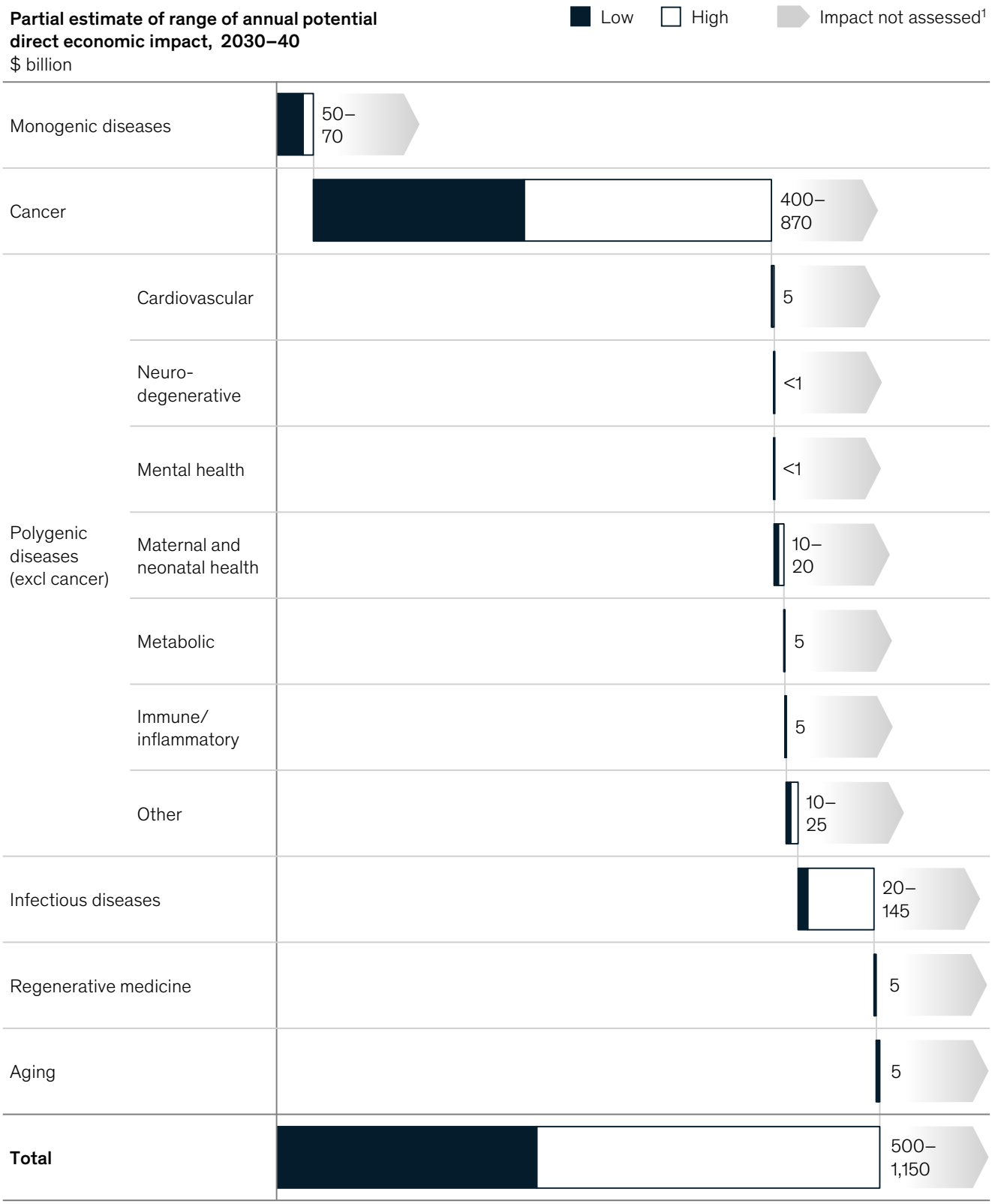
[245] The US Food and Drug Administration maintains a continually updated list of approved therapies. See *Approved cellular and gene therapy products*, FDA.

[246] Microbiomics is the comprehensive identification and quantification of the complete set of microbes (the microbiome) of a biological system (such as the human gut or skin, and in the soil around farms) at a specific point in time. See Nicolas Davis, "The human microbiome: Why our microbes could be key to our health," *Guardian*, March 26, 2018.

[247] We did not size this separately in this research because there is overlap with other treatment modalities. See Erin Brodwin, "These 9 startups are betting that your gut is healthcare's next frontier, with millions in backing from investors like Marc Benioff and Vinod Khosla," Business Insider, October 29, 2019.

Exhibit 18

The overall annual impact of using biological applications to prevent, diagnose, and treat disease could be as much as $1.2 trillion.



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.

Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.

Source: McKinsey Global Institute analysis

Monogenic diseases

An estimated 10,000 diseases affecting human beings originate from a single gene.[248] Diagnosis and treatment of these diseases is limited today by insufficient access to effective diagnostics and treatments even in cases where scientists and physicians know the precise genetic cause of the disease. Diagnostic tests for certain monogenic disorders have been available for some time. For instance, the blood test that confirms the presence of sickle cell disease was developed in 1955.[249] However, rapid and accurate diagnosis of all known monogenic disorders has become available over the past decade only because of advances in large-scale parallel DNA sequencing.[250]

Our assessment focuses on gene therapy cures that could have the greatest direct annual impact. At the time of writing, approved gene therapies exist for beta thalassemia and spinal muscular atrophy, and now trials are under way for therapies to treat other monogenic diseases, including sickle cell anemia.[251] Other diseases that can currently be treated by gene therapies include blood disorders like hemophilia and rare diseases such as inherited blindness and immune deficiencies. The availability of these therapies will reinforce screening for these disorders. Adoption of the therapies should be relatively high in high-income countries given a lack of alternative treatments and the devastating nature of the diseases. Despite expected high adoption, the overall impact is likely to be smaller than for other diseases because monogenic diseases are relatively rare.

Cancer

Cancer represents 9 percent of the global burden of disease and, in 2017, accounted for one in six premature deaths.[252] The genetic basis of cancer has been studied for at least two decades; the BRCA1 and BRCA2 mutations associated with breast cancer were first discovered in the early 1990s, for example.[253] Today, applications based on omics and molecular technologies are increasingly effective for all stages of cancer management, screening, diagnosis, staging, categorization, treatment, monitoring, and cure. The total direct impact from a range of technologies that we studied could range from about $400 million to about $870 million a year globally in the next ten to 20 years.

For decades, the primary treatments for cancer were surgery, chemotherapy, and radiation therapy. Over the past 20 years or so, drugs that target cancer cells by homing in on particular molecular changes within the tumor became standard treatments. Now, a range of gene and cell therapies are being developed for cancer. The cellular therapies apply to a diverse group of cells in the immune system, including T-cells (to which CAR T-cell therapies apply, as we discuss below), natural killer cells, dendritic cells, and other lymphocytes in the innate and adaptive immune system.[254]

Research currently focuses on a number of areas, including genetically engineered viruses that target and kill cancer cells, gene transfer to alter the functioning of and thereby kill cancer cells, and cellular immunotherapy such as cancer vaccines that enhance the ability of the body's own immune system not only to find and kill cancers, but also protect against their

[248] *Genes and human diseases*, World Health Organization; and S. Kogan et al., "Problems and challenges in patient information retrieval: A descriptive study," *American Medical Informatics Association Annual Symposium Proceedings*, 2001.

[249] *Century of progress: Milestones in sickle cell disease*, US Department of Health and Human Services, September 2010.

[250] H. Stranneheim and A. Wedell, "Exome and genome sequencing: A revolution for the discovery and diagnosis of monogenic disorders," *Journal of Internal Medicine*, January 2016, Volume 279, Issue 1.

[251] Alex Philippidis, "25 up-and-coming gene therapies of 2019," *Genetic Engineering & Biotechnology News*, May 20, 2019.

[252] Max Roser and Hannah Ritchie, *Cancer*, Our World in Data, July 2015, revised November 2019.

[253] Steven A. Narod and William D. Foulkes, "BRCA1 and BRCA2, 1994 and beyond," *Nature Reviews Cancer*, September 2004, Volume 4, Number 9.

[254] Natural killer cells are a type of lymphocyte (a white blood cell) and part of the immune system; they play a major role in host rejection of both tumors and virally infected cells. Dendritic cells are another type of lymphocyte; they process antigen material. See Sonia Guedan, Marco Ruella, and Carl H. June, "Emerging cellular therapies for cancer," *Annual Review of Immunology*, April 2019, Volume 37; Michael D. Crowther et al., "Genome-wide CRISPR–Cas9 screening reveals ubiquitous T-cell cancer targeting via the monomorphic MHC class I-related protein MR1," *Nature Immunology*, February 2020, Volume 21; and Carl H. June and Michel Sadelain, "Chimeric antigen receptor therapy," *New England Journal of Medicine*, July 5, 2018.

development in the first place.[255] That last approach is called adoptive cell transfer. The most clinically developed of the several kinds of adoptive cell transfer is chimeric antigen receptor T-cell or CAR T-cell therapy, which has grown substantially more than the others.[256] In CAR T-cell therapy, a patient's T-cells are taken from the blood, modified in the lab so that they will attack cancer cells, and then reinjected into the patient.[257]

CAR T-cell therapy is currently limited to patients with specific types of blood cancers who have not responded to other treatments; both safety considerations and affordability are holding back wider adoption.[258] In the future, use may move upstream (to patients whose disease is in earlier stages) as costs come down and safety improves.

Identification of biomarkers also facilitates early diagnosis and targeted therapy of cancers through liquid biopsies.[259] There is considerable investment in this approach because of its potential to estimate the size of tumors, select the right treatment, monitor the progress of that treatment, and detect recurrence—all using a simple blood test instead of conventional tumor tissue biopsies.[260]

Finally, new treatments for solid cell cancers are emerging, with targeted therapies, checkpoint inhibitors, and other approaches such as oncolytic viruses.[261] Some companies, including Moderna, for instance, are creating individualized therapeutic vaccines for cancer. Each tailored vaccine encodes protein-containing mutations that are unique to a patient's tumor. Once injected into the patient, the vaccine has the potential to help the patient's immune system better recognize cancer cells as foreign and destroy them.[262] Such technologies are key pillars of precision or personalized medicine that increase efficacy and reduce toxicity.

Other polygenic diseases

Most diseases have a polygenic component, and applications of omics and related biomolecular techniques are helping in the prevention, diagnosis, and treatment of cardiovascular, neurodegenerative, autoimmune, metabolic, reproductive, and other diseases. These conditions impose a heavy disease burden. New applications could take a long time to materialize and have lower adoption than treatments for monogenic diseases and cancer.

Genome-wide association studies or GWAS are furthering our understanding of the link between genes and disease pathways.[263] Identification of genes—for instance, PCSK9 for cholesterol metabolism—can lead to targeting by inhibitors, siRNAs, or genome editing.[264] Polygenic risk scoring can quantify the probability of the onset of diseases such as type 2 diabetes, and intervention can then be staged to prevent the disease from developing.[265]

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255 Robert E. Hollingsworth and Kathrin Jansen, "Turning the corner on therapeutic cancer vaccines," *NPJ Vaccines*, 2019, Volume 4.

256 Jia Xin Yu, Vanessa M. Hubbard-Lucey, and Jun Tang, "The global pipeline of cell therapies for cancer," *Nature Reviews Drug Discovery*, May 30, 2019.

257 Androulla N. Miliotou and Lefkothea C. Papadopoulou, "CAR T-cell therapy: A new era in cancer immunotherapy," *Current Pharmaceutical Biotechnology*, 2018, Volume 19, Number 1.

258 Annette E. Hay and Matthew C. Cheung, "CAR T-cells: Costs, comparisons, and commentary," *Journal of Medical Economics*, 2019, Volume 22, Issue 7.

259 A biomarker is a measurable indicator such as a molecule, gene, or characteristic, by which a particular biological process can be identified.

260 Cormac Sheridan, "Investors keep the faith in cancer liquid biopsies," *Nature Biotechnology*, August 2019.

261 We did not size the potential impact. A checkpoint inhibitor is a type of drug that helps to activate a patient's immune system. This works by blocking immune checkpoint proteins that are involved in deactivating a patient's immune response. See *Immune checkpoint inhibitors and their side effects*, American Cancer Society.

262 Elie Dolgin, "Unlocking the potential of vaccines built on messenger RNA," *Nature*, October 2019, Volume 574.

263 In a GWAS, the genomes of many people with and without a particular disease are sequenced to find areas of consistent differences. If those areas are detected, this helps scientists to zero in on parts of the genome that are responsible for the risk of disease. See *What are genome wide association studies (GWAS)?*, Train Online, European Molecular Biology Laboratory European Bioinformatics Institute; and *Genome-wide association studies (GWAS),* US National Human Genome Research Institute.

264 Hassan Dana et al., "Molecular mechanisms and biological functions of siRNA," *International Journal of Biomedical Science*, June 2017, Volume 13, Number 2.

265 Miriam S. Udler et al., "Genetic risk scores for diabetes diagnosis and precision medicine," *Endocrine Reviews*, December 2019, Volume 40, Issue 6.

Omics-based biomarkers can be used to predict and monitor conditions such as glaucoma.[266] Startups, including, for example, Mirvie, are introducing blood tests that measure placental gene expression (number of RNA molecules transcribed from DNA) in the maternal blood to predict preterm births.[267]

Finally, understanding the pathways of disease development can help identify genes to be targeted to cure or mitigate chronic diseases. Startups such as Verve Therapeutics are exploring targets for gene therapies to treat heart disease.[268] Several companies, including Axovant and Voyager Therapeutics, are conducting clinical trials of gene therapies for treating neurodegenerative disorders like Parkinson's and metabolic disorders such as OTC (an enzyme) deficiency.[269] Cell therapies involving CAR T-cells are also promising in the treatment of autoimmune disorders such as multiple sclerosis.[270] Randomized controlled trials are under way to ascertain the benefits of universal newborn genomic sequencing that can be included in each baby's medical record.

Infectious diseases

Genetics influences infectious diseases in different ways, including susceptibility, pathogen identification, and treatments. For instance, having two copies of the CCR5 mutation confers resistance to HIV infection. Genomic data from patients can indicate increased risk for infectious diseases and help in early detection and prevention.[271]

On identifying pathogens, next-generation sequencing offered by several companies—Karius is one example—can be used to sequence and identify more than 1,000 pathogens, including bacteria, viruses, fungi, and protozoa, using blood plasma, and report the results in a day.[272] Quick diagnosis can enable targeted treatment and prevent adverse drug reactions.[273] Gene sequencing of pathogens is already predicting antibiotic resistance and helping to guide treatment.

Finally, new treatment methods are being developed for infectious diseases, including, for instance, gene therapy to treat HIV, which is now in clinical trials.[274] CRISPR can be used as an "antibiotic" for killing pathogens directly or through modified phages (also known as bacteriophages, these are viruses that infect and replicate within bacteria).[275] siRNA therapies are in clinical trials to treat viral diseases such as hepatitis B.[276] Another exciting application is the development of DNA-based and mRNA-based vaccines by companies like Curevac and GSK.[277]

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266 Claudia Rossi et al., "Multi-omics approach for studying tears in treatment-naïve glaucoma patients," *International Journal of Molecular Sciences*, August 2019, Volume 20, Issue 16.

267 Heli Tiensuu at al., "Risk of spontaneous preterm birth and fetal growth associates with fetal SLIT2," *PLoS Genetics*, June 2019, Volume 15, Issue 6.

268 Amirah Al Idrus, *GV leads $58.5M round for Verve, a startup looking to pit gene editing against heart attacks*, Fierce Biotech, May 7, 2019.

269 Alice Melão, "First patient dosed with VY-AADC gene therapy in Parkinson's Phase 2 trial," *Parkinson's News Today*, December 11, 2018; and *World first for gene therapy trial patient*, UHB NHS Foundation Trust Research and Innovation, February 11, 2019.

270 Qunfang Zhang et al., "Chimeric antigen receptor (CAR) Treg: A promising approach to inducing immunological tolerance," *Frontiers in Immunology*, October 2018, Volume 9.

271 Saikou Y. Bah et al., "Highlights on the application of genomics and bioinformatics in the fight against infectious diseases: Challenges and opportunities in Africa," *Frontiers in Genetics*, 2018, Volume 9.

272 Timothy A. Blauwkamp et al., "Analytical and clinical validation of a microbial cell-free DNA sequencing test for infectious disease," *Nature Microbiology*, April 2019, Volume 4, Issue 4.

273 "Genomics soon to be standard for rapid ID diagnostics," *Infectious Disease News*, April 2018.

274 Christopher W. Peterson and Hans-Peter Kiem, "Cell and gene therapy for HIV cure," *Current Topics in Microbiology and Immunology*, 2018, Volume 417.

275 Alex Fox, "Viruses genetically engineered to kill bacteria rescue girl with antibiotic-resistant infection," *Science*, May 8, 2019; and Thomas A. Hamilton et al., "Efficient inter-species conjugative transfer of a CRISPR nuclease for targeted bacterial killing," *Nature*, October 4, 2019.

276 Alesia Levanova and Minna M. Poranen, "RNA interference as a prospective tool for the control of human viral infections," *Frontiers in Microbiology*, September 11, 2018.

277 Norbert Pardi et al., "mRNA vaccines—a new era in vaccinology," *Nature Reviews Drug Discovery*, April 2018, Volume 17, Issue 4; and N. P. Restifo et al., "The promise of nucleic acid vaccines," *Gene Therapy*, 2000, Volume 7.

Regenerative medicine

Regenerative medicine is a branch of tissue engineering and molecular biology. It refers to replacing, engineering, or regenerating human or animal cells, tissues, or organs to restore or establish natural function. Omics and molecular technologies are producing breakthroughs in this area. They hold promise for treatments that do not exist today, including for patients living with spinal cord injuries, needing organ transplant, or suffering from a range of issues from organ dysfunction to baldness. In the United States alone, there are nearly 18,000 spinal cord injuries every year, and more than 360,000 individuals living with great difficulty with the consequences.[278] The worldwide shortage of organs needed for transplants is significant. Another name is added to the transplant list every ten minutes in the United States, and, on average, 20 people die every day because of a lack of available organs.[279] In all of these cases, stem cells or acellular materials could stimulate growth or repair of such organs, as well as mitigate the immune reaction to transplantation.[280]

The largest advances have been in using stem cells in regenerative medicine. Stem cells have been applied, for instance, to spinal cord injuries, alopecia, and Crohn's disease. Some stem cell treatments secrete factors that stimulate growth or reduce immune reaction. Others grow replacement tissues. A few stem cell treatments such as bone marrow transplants for treating leukemia are well established. Conventional stem cells were derived from embryos, but more recently it has become possible to generate pluripotent (able to produce several biological responses) stem cells from adult cells. The majority of treatments to replace tissue are more novel. There have been some successes, including, for instance, growing skin for burn patients. Applications for more complex constructs such as whole, transplantable organs are on the horizon. Some initial experiments have even suggested the ability to combine 3-D-printing technologies to "print" cells into organ structures in the future (although such an application will require many more years of development).[281]

Repair of damaged tissue can also be accomplished without the use of stem cells by stimulating growth using acellular materials such as inserted scaffolds. These are composed of collagen molecules that simulate restorative cell growth in the dura mater (known as dural repair patches), a thick membrane that surrounds the brain and spinal cord. Emerging technologies also offer interesting potential for containing immune reactions to transplantation procedures themselves, including allogeneic cell therapies for controlling graft-versus-host disease and new immuno-monitoring tools.

Aging

A new field of biomedical research—geroscience—is emerging to study how molecular aging leads to disease, and to use that knowledge to slow the rate of aging and to reverse its effects such as genomic instability, telomere attrition (telomere ends of chromosomes get shorter as cells divide, a sign of aging), and epigenetic alterations.[282]

While geroscience includes technologies such as calorie restriction and exercise that are beyond the scope of this report, we examined virtually all omics, including genomics, epigenomics, transcriptomics, and proteomics, that are used to study aging.[283] Epigenomics in particular has emerged as a powerful tool in tracking biomarkers to measure the process.[284] On the therapy side, innovative anti-aging therapies such as stem cell and gene therapies are being developed and tested. Stem cells may potentially regenerate and repair tissues and

[278] *Spinal cord injury statistic*s, The Miami Project to Cure Paralysis.
[279] *Facts: Did you know?* American Transplant Foundation.
[280] Jason A. Burdick et al., "Acellular biomaterials: An evolving alternative to cell-based therapies," *Science Translational Medicine*, March 2013, Volume 5, Issue 176.
[281] Sean V. Murphy and Anthony Atala, "3D printing of tissues and organs," *Nature Biotechnology*, August 2014, Volume 32.
[282] Brian K. Kennedy et al., "Geroscience: Linking aging to chronic disease," *Cell*, November 2014, Volume 159, Issue 4.
[283] João Pedro de Magalhães, Michael Stevens, and Daniel Thornton, "The business of anti-aging science," *Trends in Biotechnology*, November 2017, Volume 35, Issue 11; and Ashok K. Shetty et al., "Emerging anti-aging strategies—scientific basis and efficacy," *Aging and Disease*, December 2018, Volume 9, Issue 6.
[284] Steve Horvath, "DNA methylation age of human tissues and cell types," *Genome Biology*, 2013, Volume 14.

organs by replacing damaged or dead cells with healthy ones.[285] Thus far, no approaches have been approved that lengthen healthy life spans and restore or maintain cognitive and physical functionality.[286] Companies working on stem cell and organ replacement for anti-aging purposes include Alkahest, Longeveron, and Rejuvenate Bio.

Significant hurdles to the discovery of effective anti-aging therapies remain. One major challenge is that studies in humans using life span as a clinical endpoint take years if not decades to complete. Some work has been started to search for, and validate, "surrogate endpoints" for aging that would be acceptable to regulatory agencies; they could be tests of muscle strength or circulating cytokines (small proteins used in cell signaling).[287] In addition, various risks may be associated with anti-aging treatments, which can carry both benefits and drawbacks. Reversing the damage resulting from aging may increase the risk of cancer, for instance.[288]

Guided care

A person's genes affect how his or her body responds to medication. For example, proteins in the liver chemically alter drugs, and these changes can make the drugs more or less active in the body and can influence side effects. Even small differences in the genes of these proteins can have a big impact on a drug's safety or effectiveness. In the long term, it may be possible for doctors to select the drugs and doses best suited for each person using an individual's genomic profile, an approach called pharmacogenomics.[289] Doing so is especially important with diseases like cancers and psychiatric disorders, for which treatments are associated with a high incidence of adverse drug reaction. After the approval of the first pharmacogenomic test in 2004, several startups, such as Color Genomics, Oneome, and Genelex, began offering lab-developed tests to consumers.

In addition to pharmacogenomics, omics analyses can help reveal key mechanisms in disease development, treatment resistance, and recurrence risk, and can guide treatment decisions.[290] For example, studies have revealed characteristic gene expression (mRNA and proteins) patterns that can predict disease progression and treatment response for patients with breast cancer, colorectal cancer, glioblastoma multiforme, and non-small-cell lung cancer.[291]

Other aids that can help to guide clinical care decisions, whose impact we do not estimate, include biosensors that can detect the presence of a biomarker (for example, reengineered skin patches can be used as biosensors to detect sugar levels) and guide treatment.[292]

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285 Aleksandar Godic,"The role of stem cells in anti-aging medicine," *Clinics in Dermatology*, July–August 2019, Volume 37, Issue 4.

286 Ivonne Hernandez Schulman, Wayne Balkan, and Joshua M. Hare, "Mesenchymal stem cell therapy for aging frailty," *Frontiers in Nutrition*, November 2018, Volume 5, Number 108.

287 James L. Kirkland, "Translating the science of aging into therapeutic interventions," *Cold Spring Harbor Perspectives in Medicine*, March 2016, Volume 6, Issue 3.

288 Jean-Philippe Coppé at al., "Senescence-associated secretory phenotypes reveal cell-nonautonomous functions of oncogenic RAS and the p53 tumor suppressor," *PLoS Biology*, December 2008, Volume 6, Issue 12; and *Cellular senescence a double-edged sword: New study holds implications for aging, cancer and evolution*, Berkeley Lab, December 2, 2008.

289 Pharmacogenomics is the use of an individual's genomic profile to optimize the choice of drugs and doses by physicians. See *What is pharmacogenomics?*, National Institute of General Medical Sciences.

290 Michael Olivier et al., "The need for multi-omics biomarker signatures in precision medicine," *International Journal of Molecular Sciences*, October 2019, Volume 20, Issue 19.

291 Aleix Prat, Matthew J. Ellis, and Charles M. Perou, "Practical implications of gene-expression-based assays for breast oncologists," *Nature Reviews Clinical Oncology*, January 2012, Volume 9, Issue 1; Christine W. Duarte et al., "Expression signature of IFN/STAT1 signaling genes predicts poor survival outcome in glioblastoma multiforme in a subtype-specific manner," *PLoS ONE*, January 2012, Volume 7, Issue 1; Wenting Li et al., "High accordance in prognosis prediction of colorectal cancer across independent data sets by multi-gene module expression profiles," *PLoS ONE*, March 2012, Volume 7, Issue 9; and Johan Botling et al., "Biomarker discovery in non–small cell lung cancer: Integrating gene expression profiling, meta-analysis, and tissue microarray validation," *Clinical Cancer Research*, January 2013, Volume 19, Issue 1.

292 Kat Arney, "Change the genes to fix the skin," *Scientific American*, January 14, 2019.

Omics and molecular technologies can play an important role in improving the development and delivery of drugs

Omics and molecular technologies can help in the identification of new molecular pathways and targets for new drug molecules, in selecting patients for clinical trials, in drug repurposing and reconditioning, and in the creation of experimental and predictive models for human health and disease. New technologies can play a significant role in reducing the time and cost of drug development and testing. "Organs on a chip"—microfluidic devices lined with living human cells that replicate the architecture and functions of living human organs—are one example.[293] Combined with omics and molecular technologies data, these devices could be a high-throughput alternative to traditional animal testing for drug development and disease modeling. Improved predictive models could reduce R&D costs by more than 10 percent by improving success rates and making R&D more cost-effective. They could also narrow the gap between preclinical testing and human trials.

Today, the productivity of R&D is unsustainably low. The estimated average cost of bringing a drug to market (including drug failures) is now $2.6 billion, a 140 percent increase over ten years ago. Only about 12 percent of novel drugs entering clinical trials will successfully reach the market.[294] Support from genomics could raise the cumulative probability of success from Phase 1 trials to regulatory approval from approximately 11 to 28 percent and reduce the cost of developing a new drug by about 50 percent.[295] Selecting for patients more likely to respond to a drug reduces the necessary size of trials and therefore their cost. The total estimated annual global direct impact of all the technologies described could be between roughly $15 billion and $25 billion over the next ten to 20 years.

[293] Boyang Zhang et al., "Advances in organ-on-a-chip engineering," *Nature Reviews Materials*, August 2018, Volume 3; Nora Franzen et al., "Impact of organ-on-a-chip technology on pharmaceutical R&D costs," *Drug Discovery Today*, September 2019, Volume 24, Issue 9; and Yasmin A. Jodat et al., "Human-derived organ-on-a-chip for personalized drug development," *Current Pharmaceutical Design*, 2018, Volume 24, Issue 45.

[294] Joseph A. DeMasi, Henry G. Grabowski, and Ronald W. Hansen, "Innovation in the pharmaceutical industry: New estimates of R&D costs," *Journal of Health Economics*, May 2016, Volume 47; and *The pursuit of excellence in new-drug development*, McKinsey & Company, November 2019.

[295] Jakob Aptekar, Nicholas Donoghoe, Edd Fleming, Meredith Reichart, Erika Stanzl, and Kevin Webster, *Precision medicine: Opening the aperture*, McKinsey & Company, February 2019.

Genetic testing of meat
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6.2. Agriculture, aquaculture, and food

Humans have been growing crops and raising animals for thousands of years using a constantly evolving set of technologies, tools, and techniques. Since the dawn of agriculture, humans have used techniques like selective breeding to develop certain traits.[296] Recent biological advances build on this long history, giving us new tools to use in our food systems that could enable a leap to entirely new business models and value chains, shift methods of production, and introduce new forms of genetic variation. In this section, we discuss a range of biomolecules and biosystems innovations in agriculture, aquaculture, and food

In the 1990s, genetic engineering emerged commercially to improve the traits of plants (such as yields and input productivity) beyond traditional breeding.[297] Historically, the first wave of genetically engineered crops have been referred to as genetically modified organisms (GMOs), or organisms with foreign (transgenic) genetic material introduced.[298] Now, recent advances in genetic engineering (such as emergence of gene editing tools like CRISPR) have enabled highly specific cisgenic changes (using genes from sexually compatible plants) and intragenic changes (altering gene combinations and regulatory sequencings belonging to the recipient plant).[299]

With the global population is expected to grow by roughly two billion by 2050, and more than 820 million people do not have enough to eat, continuing innovation is vital if we are to feed the world—and do so sustainably.[300] Food production puts a huge strain on the sustainability of natural resources. For example, raising animals for meat, eggs, and milk generates 14.5 percent of GHG emissions, according to the United Nations Food and Agriculture Organization (FAO).[301]

Biological sciences could help meet these challenges in a number of ways, including marker-assisted breeding, genetic engineering, application of insights from microbiome sequencing, and modification of the microbiome through new treatments.[302] In addition, there is potential in developing alternative proteins and using omics to improve food safety approaches. The timing of adoption will vary (Exhibit 19). Genetic editing through CRISPR is being applied to food, although this process is still at a relatively early stage. Novel plant-based protein has already been commercialized. In the United States, plant-based protein sales grew by 14 percent in 2019 versus the previous year, hitting $1 billion; in comparison, meat sales were virtually stagnant at growth of 0.8 percent.[303] Lab-grown meat is at an earlier stage; its science and production are more complex, and it remains expensive compared with traditional meat from animals.

[296] Ania Wieczorek and Mark G. Wright, "History of agricultural biotechnology: How crop development has evolved," *Nature Education Knowledge*, 2012, Volume 3, Issue 10.
[297] National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*, Washington, DC: The National Academies Press, 2016.
[298] Kaare M. Nielsen, "Transgenic organisms—time for conceptual diversification?," *Nature Biotechnology*, March 1, 2003, Volume 21.
[299] National Academies of Sciences, Engineering, and Medicine, *Genetically Engineered Crops: Experiences and Prospects*, Washington, DC: The National Academies Press, 2016.
[300] *The state of food security and nutrition in the world*, Food and Agriculture Organization of the United Nations (FAO), 2019; and Yuval Eshed and Zachary B. Lippman, "Revolutions in agriculture chart a course for targeting breeding of old and new crops," *Science*, November 8, 2019, Volume 366, Issue 6466.
[301] P. J. Gerber et al., *Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities*, Rome, Italy: FAO, 2013.
[302] *20 success stories of agricultural innovation from the Innovation Fair*, The International Symposium on Agricultural Innovation for Family Farmers, FAO, 2018.
[303] Jacob Bunge and Heather Haddon, "Plant-based meat makers compete on price," *Wall Street Journal*, March 3, 2020.

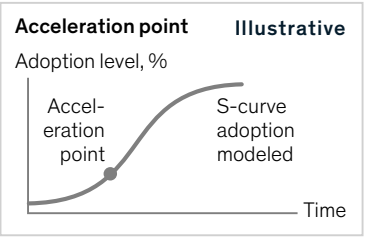
Exhibit 19

For applications in agriculture, aquaculture, and food, timing of adoption varies.

Example use cases **Not exhaustive**

Estimated time horizon of acceleration point of use cases in agriculture, aquaculture, and food
The acceleration point is when adoption starts to experience rapid growth[1]

Existing Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
Marker-assisted breeding (crops) Marker-assisted breeding (animals used for food) Genetic tracing of food origin, safety, and authenticity (eg, allergens, species, pathogens) Genetically engineered crops—resistance to droughts	Crop microbiome diagnostics and probiotic treatments Soil microbiome diagnostics and microbial seed treatments Water microbiome diagnostics and microbial water treatments (eg, microalgae-based oral vaccine for aquaculture) Genetically engineered crops—improved input efficiency (eg, irrigation water use) Plant-based proteins (eg, meat, dairy, eggs)	Genetically engineered crops and animals used for food—extended shelf life of food products Genetically engineered crops and animals used for food—disease resistance/control Genetically engineered crops and animals used for food—higher nutritional contents, better taste, specific shapes Cultured meat Genetically engineered animals used for food—faster growth Genetically engineered animals used for food—reduced greenhouse gas emissions	Genetically engineered crops—enhanced photosynthesis



1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.

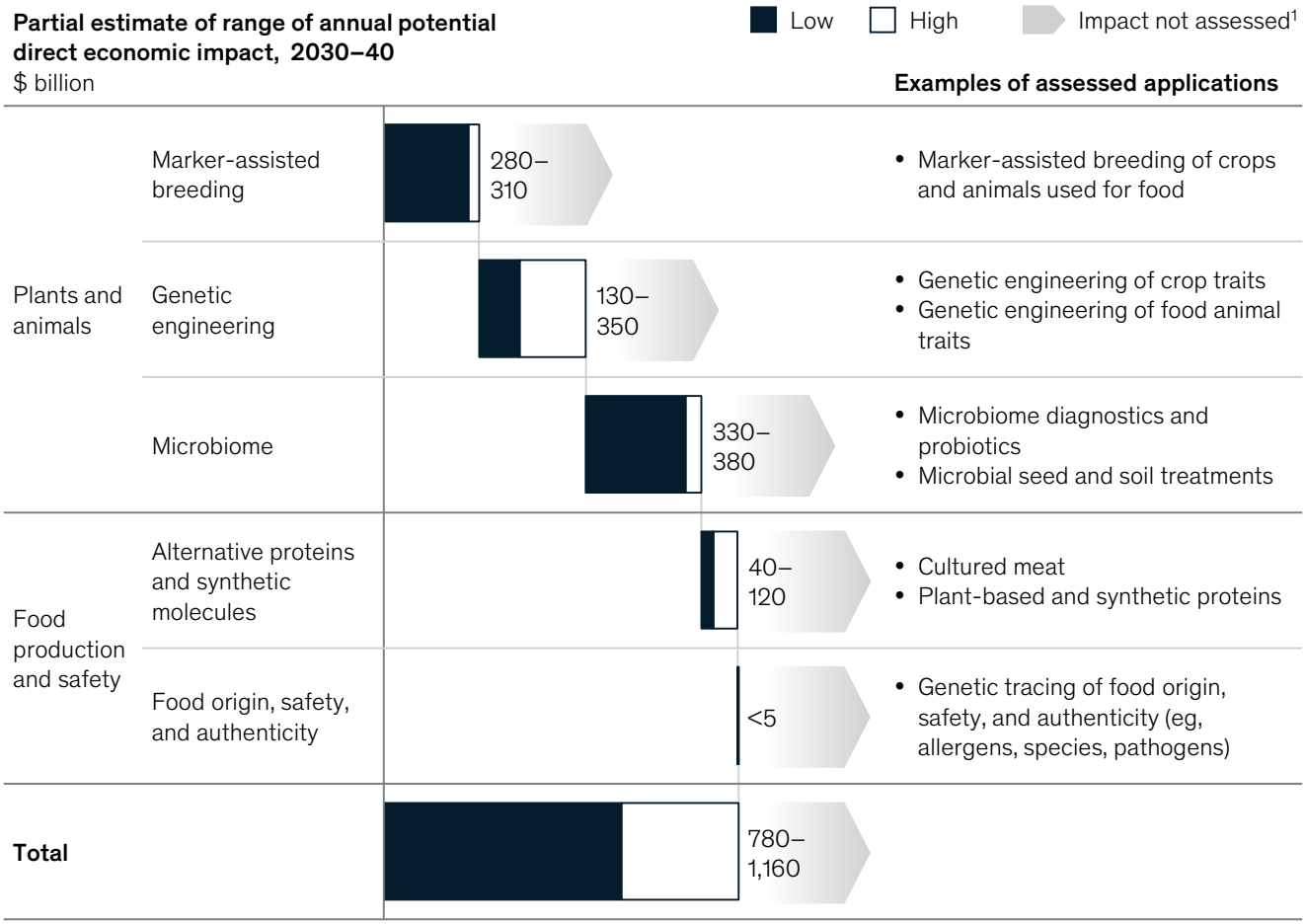
Source: McKinsey Global Institute analysis

The estimated annual direct impact from biomolecules and biosystems over the next ten to 20 years in agriculture, aquaculture, and food could be $800 billion to $1.2 trillion globally, which is 36 percent of the total direct impact from our library of about 400 use cases (Exhibit 20). For comparison, food and agribusiness is a $5 trillion global industry today.[304]

[304] Lutz Goedde, Maya Horii, and Sunil Sanghvi, *Pursuing the global opportunity in food and agribusiness*, McKinsey & Company, July 2015.

Exhibit 20

Annual impact of $0.8 trillion to $1.2 trillion in agriculture, aquaculture, and food could be created in the next ten to 20 years.



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.
Source: McKinsey Global Institute analysis

Three types of bio innovation could transform farming

In agriculture and aquaculture, we highlight three areas: marker-assisted breeding, genetic engineering, and the microbiome.

Marker-assisted breeding

Selective breeding of animals and plants is well established. In the case of plants, the semidwarf characteristic was developed first for wheat in Mexico from the mid-1940s to 1950s, and it now accounts for 99 percent of global wheat acreage. Among its advantages over normal wheat are that the stalks are shorter and stronger (and less likely to bend over in the wind, leaving the ear on the ground where it will spoil), that it takes less time to produce grain, and that it can be harvested by heavy machinery.[305] The semidwarf characteristic was subsequently bred into several types of modern rice, leading to high-yield varieties. More is to come. For example, Bayer has developed a hybrid dwarf maize variety called short stature

[305] *Semi-dwarf wheat: The game changer*, Crop Life International, July 6, 2016.

corn that is biofortified with increased beta-carotene; the company says it will demonstrate the product to growers over the next two to three years.[306]

Traditional selective breeding used visible or measurable traits, or phenotypes—an approach that was slow and costly. Now marker-assisted breeding, which identifies genes using genetic markers, is coming to the fore; this technique is multiple times faster than old-style selective breeding. In the past, developing new varieties of crops could take 25 years, but marker-assisted selective breeding has cut that down to seven to ten years at the same time that it makes selection more efficient, achieving more precision and lowering costs.[307]

Advances have been built on the back of radical reductions in the cost of DNA sequencing. Tools like high-throughput microarrays have enabled the detection of the expression of thousands of genes simultaneously, and new generations of sequencing technology are even more powerful. Modern marker-assisted breeding is better at selecting target genotypes and can be used as a replacement for phenotyping; farmers and scientists no longer need to wait for the plant to grow and then observe before selecting the target gene or multiple genes. The number of lines that need to be tested is reduced, which enables more efficient use of greenhouse or field space.

The use of genetic markers for prescreening animals for desired traits has also been successful in animal breeding. In the animal-genetics market, just one of the leading players, Neogen, genotyped more than two million animals in 2017.[308]

Marker-assisted selection is fairly commonplace in developed countries, but it is less prevalent in developing countries, demonstrating an opportunity.[309] With ever-increasing amounts of plant and animal DNA sequencing data and low-cost predictive microarrays that support high-volume population screening for genetic variation, marker-assisted selection could become universal in ten to 20 years, leading to an annual direct economic impact of about $300 billion through improved traits that can lower operating costs.

Genetic engineering

The first genetically engineered plant was tobacco, reported in 1983.[310] In 1994, the FDA approved the first genetically engineered crop, the Flavr Savr tomato, which was introduced commercially later that year and met with high demand because of its delayed ripening.[311] Demand for the tomatoes remained high for a considerable period, but the product was never profitable due to high production and distribution costs. Other genetically engineered crops have been adopted rapidly in many countries—indeed, genetic engineering has become the fastest-adopted crop technology in the world. Today, genetically engineered crops cover 12 percent of cropland, more than half of it in developing countries.[312]

306 Gil Gullickson, "Short-stature corn on the way from Bayer CropScience," *Successful Farming*, January 8, 2019.

307 In marker-assisted breeding, individual traits (such as disease resistance or quality) can be selected based on a marker, which can be morphological, biochemical, or a variation of DNA or RNA. Marker-assisted breeding uses conventional breeding approaches and does not involve transgenic approaches. See Jean-Marcel Ribaut and David Hoisington, "Marker-assisted selection: New tools and strategies," *Trends in Plant Science*, June 1998, Volume 3, Issue 6; and Bertrand C. Y. Collard and David J. Mackill, "Marker-assisted selection: An approach for precision plant breeding in the twenty-first century," *Philosophical Transactions of the Royal Society B, Biological Sciences*, February 2008, Volume 363, Issue 1491; *Molecular breeding and marker-assisted selection*, International Service for the Acquisition of Agri-biotech Applications, Pocket K Number 19, May 2006; Elcio Guimarães et al., eds., *Marker-assisted selection: Current status and future perspectives in crops, livestock, forestry and fish*, FAO, 2007; and Michael K. Osei et al., *Marker-assisted selection (MAS): A fast-track tool in tomato breeding*, November 5, 2018.

308 *High-throughput genotyping informs selective livestock breeding*, Illumina, May 2017.

309 Michael K. Osei et al., *Marker-assisted selection (MAS): A fast-track tool in tomato breeding*, November 5, 2018.

310 Kenneth A. Barton et al., "Regeneration of intact tobacco plants containing full-length copies of genetically engineered T-DNA, and transmission of T-DNA to R1 progeny," *Cell*, April 1983, Volume 32, Issue 4.

311 G. Bruening and J. M. Lyons, "The case of the FLAVR SAVR tomato," *California Agriculture*, July 2000, Volume 54, Number 4.

312 Elisa Pellegrino et al., "Impact of genetically engineered maize on agronomic, environmental and toxicological traits: A meta-analysis of 21 years of field data," *Scientific Reports*, February 2018, Volume 8.

The first wave of genetically engineered crops focused on engineering input traits (for instance, insect and herbicide tolerance) that affect farm practices such as the use of chemicals. In the current wave, the focus increasingly is on engineering output traits that affect characteristics relevant after harvest, such as prolonged shelf life. This could reduce food waste or loss through handling, with benefits to producers, processors, retailers, and consumers. There is some interest today in genetically engineered crops for consumer-facing traits, such as improved health and biofortification to increase nutrient density.

New technologies, including CRISPR and TALEN, enable more precise gene editing of plants and animals. In the case of crops, they can be tailored to local conditions such as humidity, soil type, salinity, and temperature. Gene editing could improve R&D costs and time, and could also shorten the regulatory timeline in some regions. For example, Inari is a startup that is in the early stages of using CRISPR to personalize seeds for farmers. It aims to develop seeds customized with the traits that help a crop grow best in particular local conditions such as humidity, temperature, and soil type.[313]

To harness the advantages of new gene-editing technologies, leading agricultural-input companies are working with startups on R&D. In a collaboration and licensing agreement with Monsanto (acquired by Bayer in 2018), startup Pairwise Plants is researching gene-editing technology for corn, soybeans, wheat, cotton, and canola.[314] Players like Novozymes and Inari are striking up partnerships with established seed producers of various sizes that have long-standing relationships with farmers and growers to introduce omics-driven innovations. Novozymes continued its partnership to commercialize microbial solutions with Bayer for corn and soy, and in 2019, it also pursued a multipartner model to work with other companies in the space.[315]

CRISPR-edited produce could land on grocery store shelves in the United States over the next ten years.[316] One of the first items to be sold could be sweeter strawberries with an extended shelf life. Innovation in shelf life in a broader range of food products could make a significant contribution to the global food supply given that roughly one-third of the food produced in the world for human consumption every year—approximately 1.3 billion tons—is lost or wasted.[317] Extending shelf life and reducing signs of spoilage are especially likely to reduce food waste in industrialized countries, where more than 40 percent of losses occur at the retail and consumer levels. In contrast, in developing countries 40 percent of losses occur at the post-harvest handling, storage, and processing stages.[318]

It is worth noting innovations beyond genetic engineering that combat plant disease and increase shelf life. Portable DNA sequencing devices and other advances in biosensor technology (such as CRISPR–Chip) show potential for use by farmers to diagnose plant diseases, which would eliminate the need for mass use of pesticides.[319] Researchers on the CRISPR–Chip project, conducted by Cardea, say it will take about five years of research to find the right biomarkers, create the right chips, and then develop a device that's durable enough to be used in the field.[320]

313 Frank Vinluan, *Inari Agriculture sprouts with plans to gene edit "personalized seeds,"* Xconomy, July 18, 2018.
314 Monsanto agreed to contribute $100 million to access and develop Pairwise IP in row crop applications with the option of commercializing products that emerge from the research. See *Monsanto and Pairwise announce R&D collaboration to accelerate innovation in agriculture with gene editing*, Monsanto, March 20, 2018.
315 Michael McCoy, "Novozymes and Bayer end BioAg microbe alliance," *Chemical & Engineering News*, April 12, 2019.
316 Cathy Siegner, *Monsanto invests $125M in gene-editing startup Pairwise Plants*, Food Dive, March 28, 2018.
317 *SAVE FOOD: Global initiative on food loss and waste reduction*, FAO.
318 Ibid.
319 CRISPR-Chip is a system that immobilizes CRISPR complexes on the surface of graphene-based transistors, which allows for the electronic identification of specific target genes.
320 Christie Rizk, *CRISPR–Chip shows potential for disease DX, agricultural, research applications*, GenomeWeb, August 30, 2019.

Genetic editing to alter health and productivity in food animals such as dairy and beef cattle, swine, and poultry is still nascent. The first seafood from genetically enhanced production systems—AquaBounty's AquAdvantage salmon, which grows twice as fast as normal salmon—was approved in the United States in November 2015 and six months later in Canada.[321] However, the introduction of the salmon to US consumers was delayed due to questions about appropriate labeling. The FDA approved an animal-drug application for genetically engineered salmon eggs in the United States in 2019, roughly 30 years after the initial development in the laboratory of AquAdvantage salmon.[322]

More recently, researchers have genetically engineered new traits of resistance against common diseases among animals, such as porcine reproductive and respiratory syndrome in pigs.[323] The same approach was employed to produce more flavorful beef.[324] Outbreaks of disease such as African swine fever in 2019 have generated interest in new approaches to protect farm animals, including genetic engineering. In the near term, however, responses are more likely to be in the form of conventional vaccines rather than genetically engineered immunity. Overall, genetically engineered plant and animal production systems could generate annual direct impact of about $130 billion to $350 billion through reduced mortality, improved productivity, and higher-quality outputs in taste and nutrition content over the next ten to 20 years. Consumer acceptance will be key; public sensitivity surrounds genetically engineering animals (and crops), particularly for human consumption, which can shape adoption.

Microbiome mapping and modification

In addition to breeding and genetic engineering, the discovery and development of the full potential of microorganisms—bacteria, fungi, and viruses—has become an increasingly important focus of biological research. The microbiome of plants, soil, animals, and water also plays an important role in agricultural production. Applications in this area could make a significant contribution to improving the resilience of crops, reducing losses from drought, pests, and disease, and improving yields by, for instance, enabling plants to assimilate nutrients. In a world in which climate risk is rising and food insecurity continues to be a significant challenge, such capabilities could be highly beneficial. One company founded in 2014, Indigo, offers seed treatments based on naturally occurring microbes such as plant-friendly bacteria or fungi, which farmers apply to their seeds as a spray or powder coating before planting. Another example is Novozymes, which demerged from the pharmaceutical company Novo Nordisk and offers genetically engineered microbes (among other products) instead of traditional chemicals to improve yield and quality.[325]

Companies have been using high-throughput sequencing and machine learning to develop insights on microbial species in soil and help growers be more precise and economical in choosing seeds and other inputs. Similarly, sequencing, benchmarking, and restoring the gut microbiome of food-producing animals may improve feed utilization and can potentially improve animal health. For example, Novozymes offers probiotics to stabilize the gut flora of poultry, and CoreBiome offers large-scale microbiome sequencing and benchmarking. Given that fertilizer, chemicals, and animal feed make up a significant share of operating costs in agricultural production, these innovations could create annual direct impact of about $330 billion to $380 billion globally in the next ten to 20 years.

[321] Emily Waltz, "First genetically engineered salmon sold in Canada," *Scientific American*, August 7, 2017.
[322] *AquAdvantage Salmon*, US Food and Drug Administration, March 2019.
[323] "Gene-edited pigs are resistant to billion-dollar virus," *Science Daily*, June 20, 2018.
[324] Richard Gray, "Cows genetically modified to improve flavour," *Telegraph*, August 26, 2012.
[325] Novozymes annual report, 2000.

Innovative approaches in food production and safety could change what we eat

Consumer interest in alternative protein sources is increasing globally due to concern about health, the environment, and animal welfare. An analysis of consumer search queries on Google found that cultured meat and new generations of plant-based meat substitutes have been attracting increasing interest. Sales grew at a compound annual rate of 19 and 29 percent, respectively, between 2004 and 2019. Emerging companies are developing alternative proteins that replicate the meat-eating experience. By 2030, a large share of consumers may regard eating meat from animals as immoral.[326] Consumer attitudes are already shifting about proteins from conventional animal sources. While there is an opportunity to generate healthier and more nutritious food, plant-based meats available today are primarily designed to compete with conventional meats in taste.

In this section, we look at innovation in the production of animal proteins as well as the role biology can play in improving food safety standards. Overall, there could be direct annual impact of about $40 billion to $125 billion over the next ten to 20 years.

Alternative proteins

Attitudes toward the type of food we eat are changing. Consumer awareness and interest in plant-based meat or lab-grown meat is growing, often motivated by concerns about health, animal welfare, and the environment.

Plant-based meat is derived from protein-rich seeds such as soy, chickpea, and rapeseed. The taste and texture of these alternatives is getting closer to that of animal proteins as producers expand their core market from vegetarians and vegans to include meat eaters. Impossible Foods, for example, uses genetically engineered yeast to ferment heme, an iron-containing blood molecule that imparts a metallic taste. Plant-based milk (products free of milk proteins) took off in the mid-2000s and now accounts for about 15 percent of retail milk sales in the United States and 8 percent in Britain.[327] Perfect Day Foods genetically engineers microflora to ferment plant sugar into the dairy proteins whey and casein to make animal-free milk, cheese, yogurt, and ice cream.[328] A key impediment to broad adoption in this area is the challenge of producing cost-efficiently at scale. While alternative proteins may have significant potential, the market is still nascent, accounting for only 2 percent of the global protein retail market, according to several estimates. Adoption of alternative proteins at scale will depend heavily on their cost competitiveness and consumers' taste preferences.

Several companies are rolling out new technologies and ingredients for the production of alternative proteins. Cultured meat and seafood are made using tissue-culture technology, a lab process by which animal cells are grown in vitro. This process creates muscle tissue that mimics animal muscles and has the same protein profile. Cultured meat and seafood are not yet available for purchase, but over the next ten years they could become cost competitive with conventional animal production systems. Producers still face a major technical challenge in finding a cost-effective way of growing cells. New players such as Finless Foods, Mosa Meat, Memphis Meats, and Meatables are currently experimenting with different approaches, including using synthetic molecules and pluripotent (the ability to produce several biological responses) stem cells to replace expensive growth factors.[329] The price of cultured meat has already plunged from more than $300,000 for the first lab-grown hamburger in 2013 to about $11 in 2015.[330] Products in development include lab-grown crustaceans from new

[326] "The future of food: Meatless?," *The next normal: Perspectives on the future of industries*, McKinsey & Company, October 2019.
[327] "Plant-based meat could create a radically different food chain," *Economist*, October 12, 2019.
[328] *How we do it*, Perfect Day.
[329] Matt Reynolds, "The clean meat industry is racing to ditch its reliance on foetal blood," *Wired*, March 20, 2018.
[330] Neil Stephens, Alexandra E. Sexton, and Clemens Driessen, "Making sense of making meat: Key moments on the first 20 years of tissue engineering muscle to make food," *Frontiers in Sustainable Food Systems*, July 2019; Muhammad Sajid Arshad et al., "Tissue engineering approaches to develop cultured meat from cells: A mini review," *Cogent Food & Agriculture*, 2017, Volume 3, Issue 1; Ariel Schwartz, "The $325,000 lab-grown hamburger now costs less than $12," *Fast Company*, January 4, 2015; and Amelia Lucas, "Lab-grown meat start-up raises $14 million to build production plant," CNBC, October 10, 2019.

players like Singapore-based Shio Meats, which is already trying out its lab-grown shrimp in dumplings.[331] Today, the alternative protein market (for land and sea) is valued at $2.2 billion, compared with a global meat market of about $1.7 trillion, according to the FAO.[332]

A shift to alternative proteins could have important environmental repercussions. Food production, from growing rice to raising livestock, is a primary source of anthropogenic methane, a GHG that is estimated to be about 85 times as potent as CO_2 on a 20-year time frame. According to the largest meta-analysis of global food systems to date, which used data from more than 38,000 commercial farms in 119 countries, plant-based foods generate far fewer emissions than meat and dairy from livestock.[333] The Impossible Burger, which is made from plant-based proteins, produces about 97 percent fewer GHG emissions than traditional beef, which is the most resource-intensive type of meat.[334] Cultured meat could reduce GHG emissions by 80 percent or more compared with conventional meat if all the energy used in manufacturing comes from carbon-free sources.[335] If, however, the energy required for manufacturing cultured meat comes from carbon-intensive sources such as fossil fuels, reductions in GHG emissions would be limited.[336] The production of alternative proteins could significantly reduce land and water use, compared with conventional meat production processes. The land used for meat production could be repurposed to conserve habitats and protect biodiversity. Habitat conservation and reforestation also contribute to mitigating climate change.

The rising consumption of seafood is exerting significant pressure on the marine environment. Overfishing is driving many fish species to the brink of extinction, endangering marine biodiversity and ecosystems.[337] Production of alternative proteins could help to alleviate pressure on the marine environment, but it would need to be conducted on a far larger scale than the current level.

Genetic tracing of food origin, safety, and authenticity

Food safety is a significant issue. According to WHO estimates, almost one in ten people (600 million people) in the world fall ill because of eating contaminated food and more than 400,000 die every year.[338] DNA testing of raw and processed foods can provide insights about food safety and quality; allergens, genetically engineered content, and species can be identified using genetic markers. FoodChainID (formerly Global ID), founded in 1996, was one of the first labs to employ DNA bar-coding technology along the value chain to reduce food fraud and mislabeling. The initial focus was mainly on fish-based products. New players such as Clear Labs are taking advantage of DNA sequencing and other technologies and report that they can shorten turnaround times on testing for food safety from three to five days to 24 hours as well as build searchable databases for food safety.[339] Consumers increasingly want to know what is in their food.

[331] Matt Craze, "Shiok Meats says lab-grown shrimp meat will be on the market in two years," *Undercurrent News*, September 12, 2019.
[332] Zafer Bashi, Ryan McCullough, Liane Ong, and Miguel Ramirez, *Alternative proteins: The race for market share is on*, McKinsey & Company, August 2019.
[333] For instance, producing 100 grams of protein from peas emits 0.4 kilogram of CO_2 equivalents, whereas producing 100 grams of protein from beef generates 35 kilograms of CO_2 equivalents—95 times higher. See J. Poore and T. Nemecek, "Reducing food's environmental impacts through producers and consumers," *Science*, June 1, 2018, Volume 360, Issue 6392.
[334] "Plant-based meat could create a radically different food chain," *Economist*, October 12, 2019.
[335] H. L. Tuomisto and M. J. de Mattos, "Environmental impacts of cultured meat production," *Environmental Science & Technology*, July 15, 2011, Volume 45, Issue 14.
[336] John Lynch and Raymond Pierrehumbert, "Climate impacts of cultured meat and beef cattle," *Frontiers in Sustainable Food Systems*, February 19, 2019.
[337] Allie Wilkinson, "Overfishing could push European fish species into extinction," *Science*, June 3, 2015.
[338] *Food safety*, World Health Organization fact sheet, www.who.int/news-room/fact-sheets/detail/food-safety.
[339] Lydia Mulvany, "Tyson Ventures invests in food safety testing firm clear labs," *Bloomberg*, April 11, 2019.

Biological specimen
© BSIP/Getty Images

6.3. Consumer products and services

Increasing amounts of human omics data are rapidly opening new doors for the personalization and marketing of products and services based on the biological makeup of consumers. The speed of adoption is uncertain, partially because of widespread concern about data privacy and consumer safety (Exhibit 21). In this section, we discuss a range of biomolecules and biosystems innovations in consumer products and services. There are also advances in biomachine interfaces relevant in consumer products and services, which we discuss in chapter 6.6.

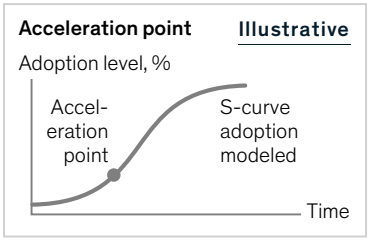
Exhibit 21

For applications in consumer products and services, timing of adoption varies.

Example use cases **Not exhaustive**

Estimated time horizon of acceleration point of use cases in consumer products and services
The acceleration point is when adoption starts to experience rapid growth[1]

Existing Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
DTC genetic testing—ancestry	DTC genetic testing—personal insights about health and lifestyle Personalized dating services based on genetic profile Personalized meal services based on genetic and microbiome profile Personalized probiotics and vitamins based on genetic and microbiome profile Pet genetic testing (eg, breed) and gene therapies Pet microbiome testing and microbial treatments (eg, fecal transplant) Genetically engineered pets Microbial skin care products	Microbial teeth whitening products Biosensors for monitoring of personal health, nutrition, and fitness based on omics data	Gene therapy—enhanced athleticism Gene therapy—hair loss Gene therapy—skin aging



1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.

Source: McKinsey Global Institute analysis

The falling cost of DNA sequencing has enabled the most mature genomic and microbiome-based applications. Of the two, genomic-based consumer applications are further ahead because genomics research is more advanced than work based on the microbiome. Early DTC genetic tests focused on nonmedical uses, such as ancestry testing in the United States in 2000. DTC genetic testing for the risk of certain health conditions became available later partly because there was a need to provide stronger evidence of linkage between genetic data and health conditions in the United States, as required by the FDA. Adoption on a large scale remains far from certain given that the medical value of DTC testing is so far unproven—and that consumer privacy concerns are high. DTC microbiome testing is nascent but developing. Scientists are beginning to make headway in understanding how the microbiome affects consumer wellness. In the coming few decades, we might see adoption of various microbiome applications such as microbiome-friendly skin-care products that contain live bacteria. Adoption by consumers of applications based on other omics (such as personalized diet based on proteomics) is further behind genomics and microbiome-based applications, given the state of the science and high costs.

Overall, the estimated annual direct impact from biomolecules and biosystems over the next ten to 20 years in consumer markets could be $200 billion to $700 billion globally, or 16 percent of the total impact estimated from the roughly 400 use cases identified in our research (Exhibit 22). This potential stems from applications such as personal insights based on DTC genetic and microbiome testing and the subsequent personalization of related products and services such as advanced probiotics covering everything from gut health to weight loss to skin care.

Biomolecules and biosystems could be applied to consumer products and services in four broad areas

Biomolecules and biosystems innovations are being applied in four broad areas of consumer products and services: DTC genetic testing, wellness, beauty and personal care, and pets and pet care. We discuss additional consumer applications, including stress-monitoring headbands, brain-controlled gaming platforms, and other wearables in the later section on biomachine interfaces.

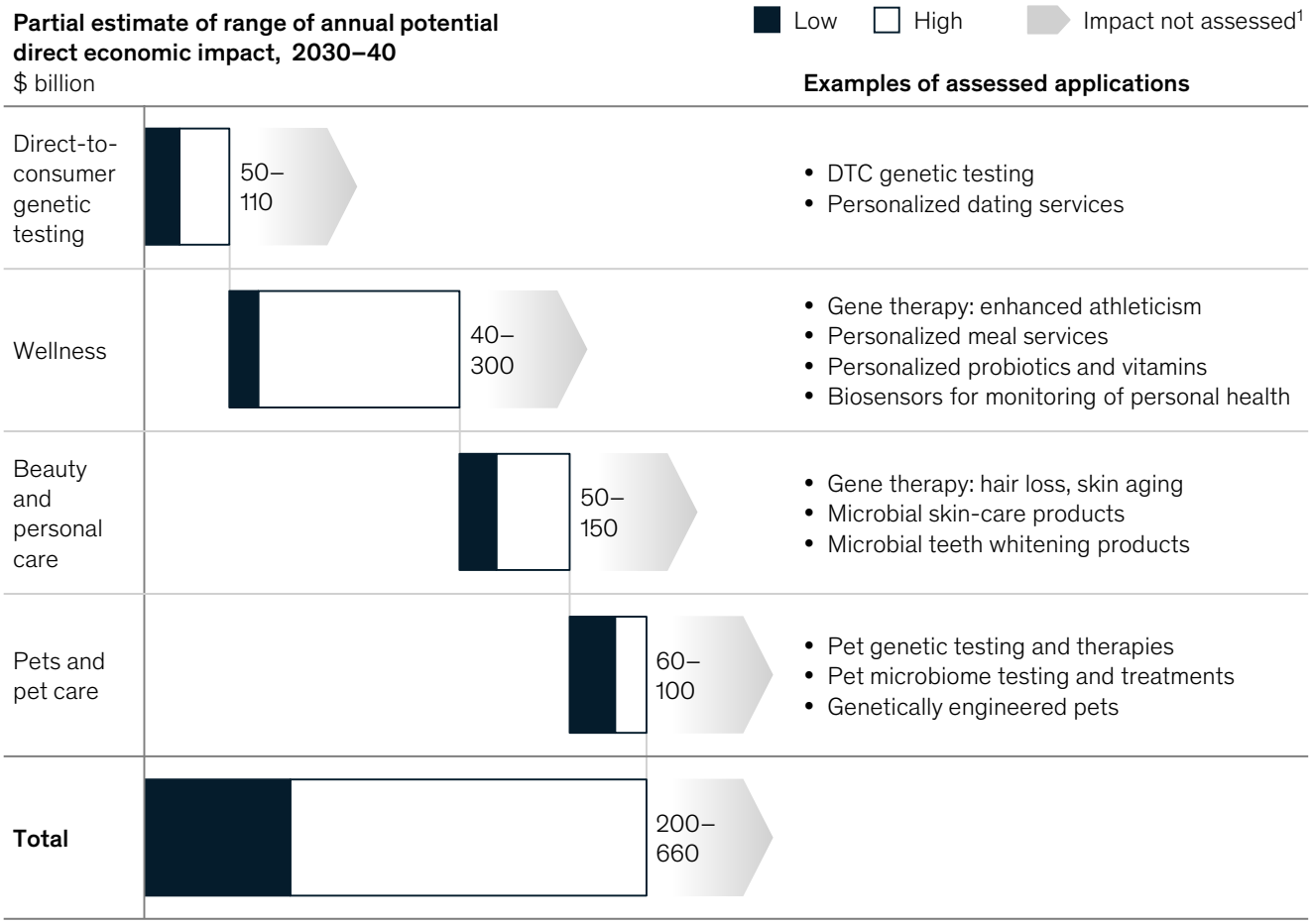
DTC genetic testing

The completion of the Human Genome Project in 2003 generated enormous demand from individuals for information about their genetic makeup. The emergence of DTC genetic testing in the United States in the early 2000s met the demand by giving individuals access to the information directly without the involvement of medical professionals. Consumers can send a saliva sample by mail and then view the results on a website or mobile app. The expansion and evolution of DTC genetic testing is being driven by a combination of intense commercial competition, strong consumer interest, large-scale research on the effect of genetics on human traits and health, and exponential advances in DNA sequencing technology. Overall, the annual direct impact could range between roughly $50 billion and $110 billion for health-related DTC genetic testing over the next ten to 20 years.[340] However, realizing this potential depends heavily on how consumers and regulators respond to significant concerns about data privacy.

[340] See the technical appendix for details of our methodology.

Exhibit 22

Annual impact of $0.2 trillion to $0.7 trillion in consumer products and services could be created in the next ten to 20 years.



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.
Source: McKinsey Global Institute analysis

Early offerings focused on genealogy research, with Family Tree beginning ancestry testing in the United States in 2000, followed by companies such as 23andMe and AncestryDNA. By the end of 2018, more than 26 million people had taken an at-home ancestry DNA test in the United States.[341] These services expanded, exploring the potential relationship between a consumer's genetic makeup and talents, preferences, and lifestyle aspects such as fitness and nutrition. However, some of these associations are weak or questionable (and we have not included them in our impact assessment).

Second-generation DTC genetic testing, focused on genetic risk for certain health conditions, is now emerging. If the medical value can be proven and privacy and data security concerns are addressed, a new wave of users could be captured.[342] In 2017, the FDA allowed 23andMe to market DTC tests for ten conditions, including Parkinson's disease and Alzheimer's

[341] Antonio Regalado, "More than 26 million people have taken an at-home ancestry test," *MIT Technology Review*, February 11, 2019.
[342] *23andMe and the FDA*, 23andMe.

disease.[343] The FDA review led to more streamlined approval of health-related DTC genetic tests in the United States, paving the way for other startups to shift or expand their focus to health.

Most current DTC testing typically uses a method based on single nucleotide polymorphisms (SNP) analysis, which involves using a DNA microarray to detect the presence or absence of specific variations throughout the genes.[344] In SNP analysis, typically less than 1 percent of human genome is sequenced.[345] However, more comprehensive genome sequencing is becoming more popular as its cost declines due to technological advances; this, in turn, lends itself to a new business model. [346] Under a subscription-based revenue model, sequencing output can be a lifelong resource, enabling consumers to learn more and more about themselves as the pertinent science progresses. AncestryDNA's new division Ancestry Health launched its new subscription-based service that leverages next-generation sequencing in 2020.[347]

Compared with the United States, China remains a nascent market for DTC genetic testing. A program conducted by the Shanghai Biochip Corporation to predict traits such as emotional control, focus, memory, and athletic ability, among others, based on genetic testing of children, emerged in 2009.[348] 23MoFang, the largest provider of genetic testing services to Chinese consumers, had tested only about 500,000 consumers out of a population of 1.4 billion as of fall 2019.[349] However, as the cost of DNA sequencing has fallen, these tests have become increasingly affordable for the average Chinese family, and this has triggered more than 100 companies to enter the segment over the past five years.[350] They include large players like Shenzhen-based WeGene and Beijing-based Novogene. DTC players are rapidly building awareness through China's ubiquitous social media and e-commerce channels. They are increasingly tailoring their offerings to East Asian consumers who were previously underrepresented in the database of Western genetic test providers.[351]

Genome data enable new opportunities for personalization in consumer markets. The full range of what is scientifically possible is unclear, but some companies have already begun to experiment with personalized online dating to meal services, custom-tailored fitness, and other applications.[352] Companies ranging from professional services firms to app developers and retailers are offering applications based on personal biological data.

Wellness

Consumer wellness is a major area for biological applications. Regularly updated information about the gut and skin microbiomes as well as other molecules corresponding to different cellular functions may provide guidance for consumers' behavior and lifestyle. Gene editing to increase muscle mass is currently being tested by biohackers and could become commercially available in about ten years. Acknowledging that genetic data on its own tells only part of the story about consumers' biology, some startups take more holistic approaches. As with DTC genetic testing, emerging databases capturing the composition of consumers' microbiome and other variables could enable scientific advances leading to personalized

[343] In 2018, the FDA "permitted marketing, with special controls, of the 23andMe Personal Genome Service Pharmacogenetic Reports test as a DTC consumer test for providing information about genetic variants that may be associated with a patient's ability to metabolize some medications to help inform discussions with a health care provider." See *FDA authorizes first direct-to-consumer test for detecting genetic variants that may be associated with medication metabolism*, FDA, October 31, 2018.

[344] Rachel Horton et al., "Direct-to-consumer genetic testing," *The BMJ*, October 2019, Volume 367.

[345] *myGenome,* Veritas.

[346] "Now you can sequence your whole genome for just $200," *Wired*, November 19, 2018.

[347] Edward C. Baig, "Ancestry launches DNA health services that will compete with 23andMe," *USA Today*, December 16, 2019.

[348] Emily Chang, "In China, DNA tests on kids ID genetic gifts, careers," CNN, August 3, 2009.

[349] Zen Soo, "As demand for genetic testing grows in China, start-up 23Mofang can now tell you if you have royal blood," *South China Morning Post*, October 19, 2019; and *Code and capital: Genetic testing in China*, CKGSB Knowledge, February 2017.

[350] Toby Overmaat et al., "Consumer-facing genetic testing in China: A status report," *The Lancet*, October 2018, Volume 392, Supplement 1.

[351] Zen Soo, "As demand for genetic testing grows in China, start-up 23Mofang can now tell you if you have royal blood," *South China Morning Post*, October 19, 2019.

[352] We did not assess the economic impact from personalized retail recommendations based on biological data.

consumer products and new medical treatments. Overall, the annual direct impact could range from roughly $40 billion to $300 billion for wellness applications over the next ten to 20 years.

Scientists are beginning to make headway in understanding how the microbiome affects human health and disease, with much of this impact likely being mediated through diet.[353] DTC microbiome testing is nascent but developing. In a similar way to genetic tests taken at home, consumers collect a stool sample and mail it in for testing. In the future, collecting critical genetic information about microbes contained in human saliva could simply take a cheek swab. Some early commercial applications already exist. For instance, combining analysis of microbiome and blood tests, Israeli company DayTwo provides nutrition insights for people with diabetes through an app designed to maintain normal blood sugar levels.[354] Another area of interest is a new generation of probiotic and vitamin supplements customized based on an individual's microbiome rather than questionnaires about lifestyle. Microbiome-testing companies ProTrea, Thryve, and SunGenomics, for instance, offer personalized probiotic plans.

In the next few decades, it may become possible to measure and analyze an even broader set of biological information in a cost-effective and convenient manner. This could transform personal-health monitoring, especially for the elderly and people with chronic diseases, as well as the tracking of fitness and nutrition. Today's wearable devices are generally worn around the wrist. The new frontier may be patches on the skin or even ingestible sensors. Skin sensors work by detecting sweat, volatile organic compounds, microbes, or particles in the surrounding environment. Startup LogicInk has developed skin sensors that measure changes in biomarkers related to hydration and blood alcohol; this effort is at an early stage. Ingestible sensors are pill-sized electronics that can transmit data such as video, pH, temperature, pressure, and adherence to medication to a device such as a smartphone.

Beauty and personal care

Little public funding currently goes toward nonmedical gene therapies, as governments and scientists focus on curing diseases as a priority. However, if private-sector beauty and personal-care companies invest in this area and collaborate with researchers, those therapies could become commercialized before 2050. Some established beauty and personal-care companies have been conducting scientific research into the role of genomics and microbiomics in innovative anti-aging skin-care products, working in skin biology labs sometimes in collaboration with medical institutions. Some discoveries could emerge as a byproduct of research in other areas. For example, Latisse was a cataract treatment that had the side effect of making eyelashes grow. The treatment became a cosmetic eyelash solution.[355] Overall, we estimate direct annual impact of roughly $50 billion to $150 billion for skin care and oral microbiome products over the next ten to 20 years.[356]

Research into the skin microbiome is ongoing. The skin microbiome is home to roughly 1,000 species of bacteria that can not only affect the health and appearance of skin but contribute to common skin conditions such as acne and eczema as well as aging.[357] Biotech startup AOBiome's consumer division Mother Dirt is developing hygiene and personal-care products filled with live ammonia-oxidizing bacteria, which are most commonly found in dirt and untreated water. The bacteria convert irritating components of sweat (ammonia and urea) and turn them into byproducts that bring benefits to the skin. Historically, the bacteria would have

[353] "Influence of the microbiome on the metabolism of diet and dietary components," in *The Human Microbiome, Diet, and Health: Workshop Summary*, Institute of Medicine of the National Academies Food Forum, Washington, DC: National Academies Press, 2013.

[354] "DayTwo secures $31 million in series B financing to scale microbiome research platform to address chronic health conditions," DayTwo, June 26, 2019.

[355] *Latisse (bimatoprost ophthalmic) solution label*, Allergan, 2012; and Catherine Saint Louis, "Long lashes without prescription, but with risks," *New York Times*, May 1, 2010.

[356] The large range of impact for applications we sized reflects significant uncertainty about adoption.

[357] Bia Bezamat, "L'Oréal deepens scientific focus on personalization with uBiome partnership," *The Current Daily*, March 8, 2019.

populated the skin microbiome naturally, but widespread use of soaps, deodorants, and other personal-care products has significantly reduced their population.[358] Restoring those bacteria can remedy body odor or skin irritation issues, cut down on shower use and chemicals, and help in caring for wounds.[359] Established brands such as La Mer are increasingly moving into probiotics (for which there is no standardized definition), while new players such as Tula also offer probiotic skin care. However, unlike Mother Dirt's microbiome products, the vast majority of probiotics products offered today do not contain live microorganisms that require refrigerated storage.

Research is also ongoing into the relationship of the gut microbiome to the skin, referred to as the gut-skin axis. The gut may communicate with the skin in several ways, for example through the absorption of nutrients with a direct effect on the skin or those that can stimulate hormonal changes that affect the skin.[360] Viome's gut microbiome test, for example, establishes links between gut bacteria and skin conditions such as acne and eczema, blurring the line between consumer markets and healthcare. Consumers have expressed considerable concern about inflammation caused by using products that are wrong for an individual's skin. Microbiome (and genetic) testing to enable personalization and new products could have significant potential. Singapore-based genomics firm Imagene Lab, for instance, offers a personalized serum based on the results of its skin DNA tests that assess traits such as premature collagen breakdown.

Researchers are also exploring microbial solutions to improve dental hygiene and beauty procedures based on the oral microbiome. For instance, probiotics derived from the dental plaque of healthy individuals sharply antagonize cariogenic bacteria (oral bacteria that cause tooth decay). However, the high cost of conducting clinical trials and the status of dental cavities as a non-life-threatening condition could continue to impede the advancement of new therapeutics to market.[361] Oral care probiotics could also deliver cosmetic benefits such as teeth whitening. For example, a recent clinical study found that mouthwash incorporating three natural hydrogen peroxide–producing oral bacterial strains has a statistically significant whitening effect.[362]

Finding genetic cures for hair loss and skin wrinkles, rather than simply slowing down the process, is one of the most eagerly sought outcomes of innovative anti-aging skin-care companies. The most common form of genetic hair loss is androgenetic alopecia—also known as pattern hair loss—that by the age of 50 affects about half of males and one-quarter of females.[363] With gene therapy, hair follicles with DHT-sensitive cells could be changed into follicles with DHT-resistant cells, and the hair follicles would continue to grow new hairs for a lifetime.[364] However, gene therapy for cosmetic uses such as aging skin and hair loss is unlikely to have significant economic potential in the time frame we investigated. The science is not yet feasible in humans, and it is not clear whether and when products may be commercially viable given that the regulatory response is uncertain.

[358] *What are AOB?*, Mother Dirt.
[359] Rina Raphael, "How this bacteria-crawling skincare line became a fast-growing wellness brand," *Fast Company*, May 31, 2019.
[360] Raja Sivamani, "The gut-skin axis and mechanisms for communication," *Natural Medicine Journal*, August 2018, Volume 10, Issue 81.
[361] Jonathon L. Baker and Anna Edlund, "Exploiting the oral microbiome to prevent tooth decay: Has evolution already provided the best tools?," *Frontiers in Science*, January 11, 2019.
[362] Jeffrey D. Hillman et al., "Dental whitening effect of an oral probiotic," *Dental, Oral and Craniofacial Research*, 2016, Volume 2, Issue 1.
[363] Jay C. Vary Jr., "Selected disorders of skin appendages—acne, alopecia, hyperhidrosis," *Medical Clinics of North America*, November 2015, Volume 99, Issue 6.
[364] Dihydrotestosterone or DHT is a derivative of the male hormone testosterone and is thought to be the main reason for male baldness. See *Gene therapy*, American Hair Loss Association.

Pets and pet care

There is interest in applying genetic and microbiome testing, as well as personalized nutrition and precision medicine, to pets. Advances in this area could be of interest given that the global pet-care market is expected to be valued at roughly $60 billion to $100 billion by 2025.[365]

DTC genetic and microbiome testing is coming to the world of pet owners. In 2005, less than three years after the completion of the international effort to sequence the human genome, researchers published a map of the canine genome using the DNA of a boxer. Today, companies such as Wisdom Panel (a division of Mars Petcare), Embark Veterinary, and Basepaws offer home DNA tests for cats and dogs that provide insights into ancestry, breed, health predispositions, and traits.

Precision veterinary medicine is developing. For example, One Health Company is now sequencing dogs' cancer tumors and recommending targeted therapies normally used to treat humans.[366] Innovation is also advancing in the microbiome of pets. For example, AnimalBiome offers microbiome tests and supplements as well as fecal microbiome transplant capsules to replace and rebalance bacteria that are missing and restore the health of a pet's gut.[367] Overall, the estimated direct annual impact ranges from $60 billion to $102 billion for innovation in pets and pet care in the next ten to 20 years.

The GloFish brand, which estimates that it has 15 percent of the US market for aquatic fish sales, has been offering genetically engineered fluorescent fish since 2004.[368] Genetic engineering could potentially also be applied to pets to accelerate some of the crossbreeding seen today (think of breeds like the miniature goldendoodle, a cross between the golden retriever and the toy, miniature, or small standard poodle) and to address pet health problems such as allergies. Gene therapy could fix health conditions to which certain breeds are genetically predisposed, such as hip dysplasia in golden retrievers and Labradors, and heart conditions in Great Danes). In some cases, gene therapy could also improve performance of animals. For instance, in Argentina scientists have already used CRISPR to rewrite the sequence of the myostatin gene, which is crucial to muscle development, in cloned polo ponies, the most cloned animal in the world.[369] Another application that taps into human beings' emotional attachment to their pets is gene preservation and pet cloning. Pet cloning has been available for years in South Korea and the United States from companies such as ViaGen Pets and Sooam, but it has not taken off. Sinogene, a Beijing-based commercial pet-cloning company, has been cloning dogs for years and began cloning cats in 2019.[370]

[365] *Pet care market 2019: Global analysis, industry size, share leaders, current status, segments and trends by forecast to 2025*, Market Watch, July 16, 2019; and *Pet care market size worth $201.6 billion by 2025—CAGR, 4.9%*, Grand View Research, March 2018.

[366] Rebecca Robbins, *With human drugs, a Silicon Valley startup hopes to deliver precision medicine to dogs*, STAT, January 23, 2019.

[367] *How it works*, Animal Biome.

[368] Leonard Ho, "How much is GloFish worth?," *Advanced Aquarist*, September 5, 2017.

[369] Sonia Avalos, *Argentine polo turns to genetics to produce champions*, Phys Org, November 28, 2018; and Sarah Knapton, "Genetically engineered 'super-horses' to be born in 2019 and could soon compete in the Olympics," *Telegraph*, December 26, 2017.

[370] Sui-Lee Wee, "His cat's death left him heartbroken. So he cloned it," *New York Times*, September 4, 2019.

Strands of synthetic spider silk
© Kiyoshi Ota/Bloomberg/Getty Images

6.4. Materials, chemicals, and energy

Materials have played such a fundamental role in human history that historians have named entire time periods after them— the Stone, Bronze, and Iron ages. Like the invention of plastics in the 1940s and 1950s, recent biological advances in materials, chemicals, and energy could transform not only many industries but our daily lives. However, it will take time—perhaps even several generations of companies—and improved economics to realize their impact. Although many applications may see initial fast adoption in the coming ten years, most of them won't reach their full impact for a few decades (Exhibit 23). In this section, we discuss a range of biomolecules and biosystems innovations in materials, chemicals, and energy.

Exhibit 23

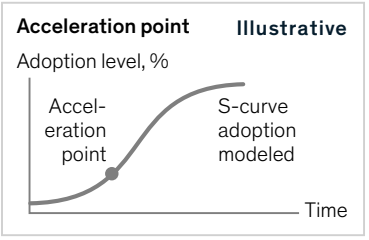
For applications in materials, chemicals, and energy, timing of adoption varies.

Example use cases

Not exhaustive

Estimated time horizon of acceleration point of use cases in materials, chemicals, and energy
The acceleration point is when adoption starts to experience rapid growth[1]

Existing Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
New bioroutes—drug manufacturing (eg, peptides)	Genetic tracing of fabric origin and authenticity	Novel materials—biopolymers (eg, PLA, PET)	Biosolar cells and biobatteries
Improved existing fermentation process—biopesticides/biofertilizers	Improve existing fermentation processes—food and feed ingredients (eg, amino acids, organic acids)	*Pipeline has limited visibility*[2]	
Improved existing fermentation processes—other (eg, hydrocolloids, fragrances, cosmeceuticals)	Improve existing fermentation processes—industrial enzymes (eg, detergent enzymes)		
	New bioroutes—food and feed ingredients (eg, stevia sweetener)		
	New bioroutes—industrial enzymes (eg, biocatalysts)		
	New bioroutes—fabrics and dyes (eg, mushroom leather, spider silk)		
	New bioroutes—other (eg, squalene)		
	Novel materials—biopesticides/biofertilizers (eg, RNAi pesticides)		
	Novel materials—chemicals (eg, IC process chemicals)		
	Extraction of raw materials through genetically engineered microbes (eg, microbial enhanced oil recovery)		
	Biofuels		



1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.
2. We have comparatively less visibility on the path ahead for novel materials and chemicals, partially because they are largely being developed by private-sector companies that want to maintain confidentiality and partially because the research and development of many novel materials is still at an early stage. Many breakthroughs in novel materials and chemicals with unknown properties are yet to come.

Source: McKinsey Global Institute analysis

Labs around the world are now using genetically engineered microbes to improve the economics of fermentation, develop new fermentation processes, and even produce novel materials with previously unimaginable properties, like the ability of fabrics to self-repair. Genetic tracing of where fabrics come from and their authenticity is another application. Advances in the production of biofuels as well as new forms of energy storage are under way. However, with few exceptions, the scale has not been as large as many promised, in part due to cost competitiveness compared to existing substitutes, challenges in scaling, and supply chain constraints. Current work in the field of energy storage has produced theoretical proofs of scientific feasibility, but applications have not yet been commercialized and scaled effectively.

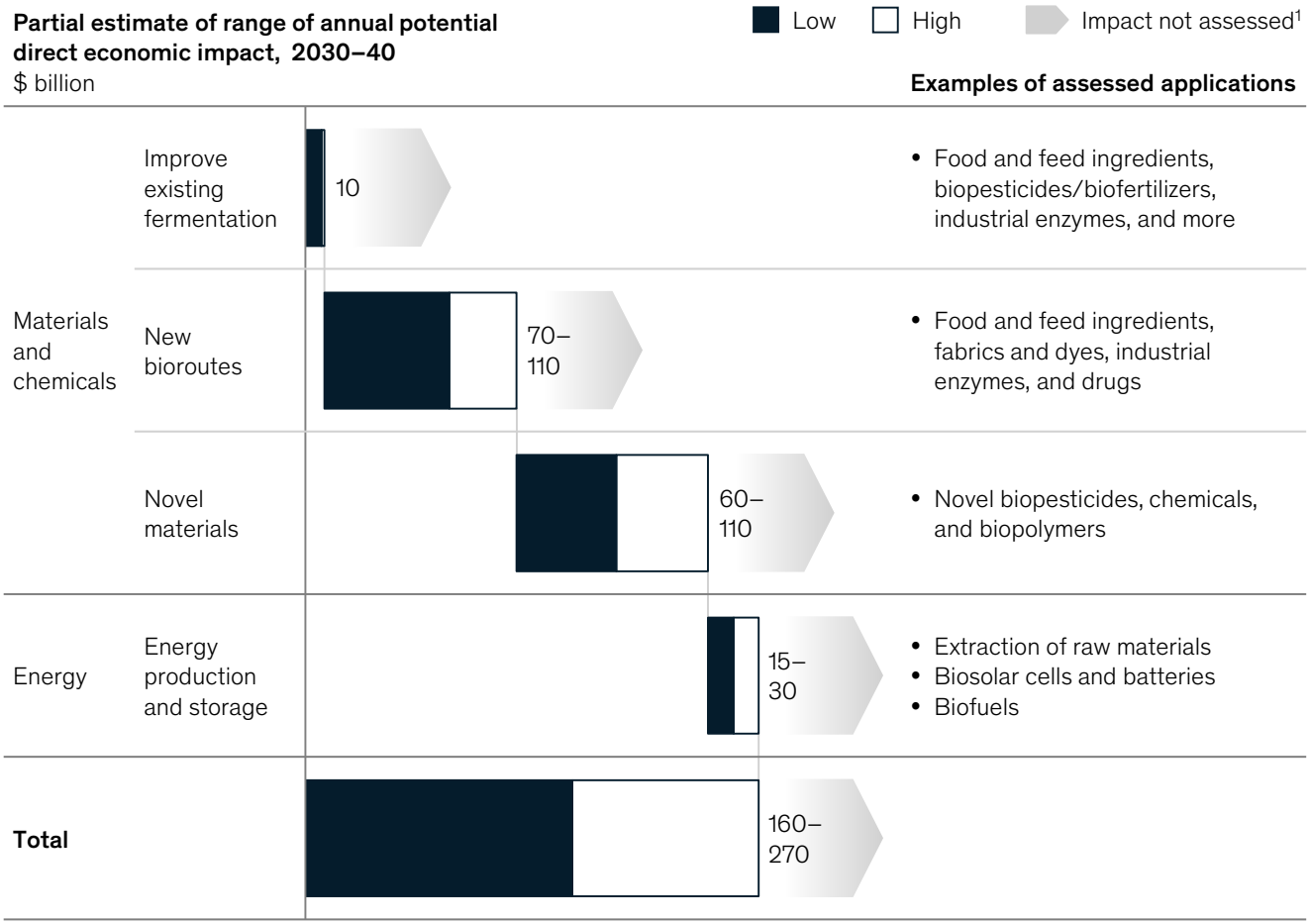
Our assumptions about the timing of adoption are conservative for a number of reasons. First, scaling new innovations in materials, chemicals, and energy has historically been difficult. Cost is often a critical factor, because the innovations may be more expensive than the commoditized established products against which they must compete, including plastics and natural gas, which also can have well-established supply chains. For example, biofuels promised to be a viable alternative to petroleum, but they have not yet come close to replacing traditional fuel. Innovation in materials production processes has been slow because of high fixed costs. Broadly speaking, biotech applications remain more expensive than petroleum-based products—particularly biofuels produced through fermentation. Although the production of hydrocarbon fuels from biomass is technically possible, reducing production costs to commercially viable levels remains a challenge. In summary, the science may be in place (the first step toward adoption), but there are still challenges here in the second step of ensuring that the economics work by creating a compelling value proposition for customers and being able to industrialize the science and scale production.

Second, enormous uncertainty about the likely impact surrounds these technologies. For example, entirely novel materials with large potential may be on the horizon, but it is difficult to anticipate (and therefore measure) this today. Many companies are likely to tailor materials to meet the unique demands of clients. Predicting all the novel materials that could be produced through biological methods, and the potential economic impact created, is challenging. Our working hypothesis is that the potential is significant.

Overall, in the next ten to 20 years, we estimate the potential annual direct impact from biomolecules and biosystems via the production of materials, chemicals, and energy using advances in biology at about $200 billion to $300 billion globally, which is 8 percent of the total direct impact from our library of about 400 use cases (Exhibit 24). The eventual economic potential of novel materials—that is, materials having new properties not currently available—could be large, although there is considerable uncertainty about which novel materials and methods may emerge. In comparison, the impact in this time frame from energy production and storage is likely to be relatively limited given the challenges of competing with the economics of traditional processes. Energy sources and storage are relatively nascent technologies, and significant impact from sized applications in the next ten to 20 years is not expected.

Exhibit 24

Annual impact of $0.2 trillion to $0.3 trillion could be created in the next ten to 20 years in materials, chemicals, and energy.



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.
Source: McKinsey Global Institute analysis

Three types of advances in materials and chemicals could affect various sectors

In materials and chemicals, we highlight three areas: improving existing fermentation processes, developing new bioroutes for the production of existing materials and chemicals, and the production of novel materials and chemicals. There is substantial potential for impact by introducing improved economics to the production of materials and chemicals, improving their quality, or both, and by producing them in a more sustainable way. In materials and chemicals, applications are increasingly seen in, or could spread to, sectors as diverse as pharmaceuticals, plastics, fragrances, fabrics, and construction.

Improve existing fermentation

The first area for potential impact is further optimizing the economics of the production of goods currently made through fermentation. Globally, many established large players active in fermentation-based production, including, for instance, Corbion, DSM, and Novozymes, are devoting significant investment to further improving their technology platforms and capabilities. In addition, over the past decade a number of new biotech companies have emerged that offer new and improved biological capabilities that further

enhance fermentation and other bioroutes for the development of products; two examples are Ginkgo Bioworks and Synthace. These newer companies are positioning themselves largely as businesses that can help incumbents improve the efficiencies and economics of existing industrial fermentation manufacturing processes and product development work. In combination, the push in this area by both incumbents and startups to improve fermentation processes could offer significant potential for cost savings in affected industries.

New bioroutes for existing materials and chemicals

Another dynamic area is new bioroutes, primarily using fermentation-based methods, to manufacture products that are difficult or costly to synthesize chemically or extract from natural resources. One industry showing promise and attracting considerable interest is textiles. In recent years, methods have been developed to produce alternative nylon, silk, cotton, and clothing dyes using biological methods. As the effectiveness of these production methods in materials and chemicals develops, new bioroutes are spreading to other subsegments of the chemicals and pharmaceuticals markets, such as cosmetics and even masonry, that have traditionally been dominated by natural extraction or chemical reactions.

For many of these industries, shifting production to bioroutes is attractive not only to capture efficiency gains but also to respond to a desire to produce more sustainably. Consider the case of nylon that has traditionally been manufactured from petrochemical components.[371] Now, a new way of producing nylon with engineered microorganisms has recently been commercialized. For example, caprolactam, a key ingredient in making 100 percent sustainable nylon, is being produced using biological means by Genomatica and Aquafil.[372] The textiles industry has many other examples of producing alternatives to current materials. Mango Materials uses waste methane to produce PHA, a polymer that is then spun into thread. In 2015, Spiber began developing a parka made from artificial spider silk. The parka did not make it to market, but four years later the company created a follow-up, using a new textile made of synthetic fermented proteins.[373] These techniques could disrupt an industry that is today valued at more than $200 billion.[374]

Similarly, the industrial manufacturing of cosmetics stands to gain from a transition to bioroutes. One prime example is the biological production of squalene, which is traditionally derived from unsustainable sources, including oil byproducts and shark livers. Amyris commercialized a sugarcane-derived substitute, which is used to produce high-end, high-performance cosmetic products. These and other renewably sourced products such as Geltor's fermentation-based collagen protein can unlock a new segment of environmentally conscious customers.[375] Fermentation-based manufacturing is also being applied to natural fragrances that are difficult to extract. For instance, Ginkgo Bioworks identified the DNA sequences of the enzymes that produce rose-oil compounds. In the past, using traditional methods, 60,000 roses were used to make 30 milliliters of rose oil.[376] This resource-heavy process has now been replaced by commercial-scale fermentation, which is more environmentally sustainable.[377]

Many of the players in these areas are still in the early stages and haven't fully scaled their technologies, manufacturing, and commercialization. However, more players, both new and existing, and investment capital are focusing on these areas to find more efficient and sustainable ways to produce products.

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[371] Stefanie Kind et al., "From zero to hero—production of bio-based nylon from renewable resources using engineered *Corynebacterium glutamicum*," *Metabolic Engineering*, September 2014, Volume 25.

[372] *Aquafil and Genomatica join forces for bio-nylon—target more sustainable apparel, carpets and fibers*, Aquafil Global, January 23, 2018.

[373] *There's now a lottery for this North Face x Spiber parka made of fermented proteins*, Highsnobiety, August 2019.

[374] *Leather goods market value forecast worldwide from 2016 until 2021 (in billion U.S. dollars)*, Statista, October 2017.

[375] Ecocert is an organic certification organization, founded in France, that certifies primarily food and food products but also cosmetics, detergents, perfumes, and textiles.

[376] Linda Baily Synovitz and Karl L. Larson, *Consumer health & integrative medicine*, Jones & Bartlett Learning, September 28, 2018.

[377] *Scaling bioprocesses*, Ginkgo Bioworks.

Production of novel materials and chemicals

Bioroutes are also being used to create entirely new materials and chemicals with superior properties such as greater strength and durability and the ability to self-repair. While still nascent, several players are already bringing novel, differentiated bio-based products to market. For example, in April 2019, Zymergen announced a partnership with Sumitomo Chemical to develop bioroutes for the development of novel bio-based building blocks for next-generation electronics.[378] The companies announced that their partnership may include applications such as optical films for displays, hard coatings that won't scratch, flexible electronics circuits, and adhesive materials.

Inputs for agriculture are developing that use bioroutes to produce improved fertilizers and pesticides. These are still in their proof-of-concept stage and earlier in their development than the bioroutes in materials and chemicals that we have noted. For example, inputs for the agricultural industry using RNAi gene silencing are being designed to establish a new kind of pesticide. The expression of a gene critical for a life function of insects is inhibited by specific RNA via spray or oral delivery.[379] The first RNAi insecticide was approved for commercial use in 2017.[380]

Innovative approaches are under way in energy production, extraction, and storage, but the timing of impact is uncertain

Some developments are taking place in the production of biofuels, the extraction of raw materials, and the storage of energy. There is potential for biology-based fuels that offer an alternative to traditional fossil fuels, thereby helping to meet growing energy demand and address global concerns about CO_2 emissions and climate change. Another area of growing interest is using biological approaches to improving energy storage, including, for instance, biology-based fuel cells and using engineered microorganisms to create advanced electrodes for next-generation batteries. However, the impact of innovation in these areas is estimated to be small, because current biological technology alternatives are not able to compete on cost and energy density with existing petroleum technologies. The pace of innovation in this field also varies. While there may be some innovations in biofuels over the next few decades, biology-based energy storage is unlikely to experience significant commercialization over the next 30 years.

Biofuels

First-generation biofuels, particularly bioethanol for transportation produced from sugars and starch, have existed for decades. Ethanol has been produced using fermentation of carbohydrates produced in sugar- or starch-bearing plants like corn or sugarcane.[381] Demand for the resulting bioethanol has been growing steadily, and this has fueled interest in improving technologies through biological advances.[382]

In the advanced biofuels industry, a number of innovations may eventually have an impact on the transportation industry. Some companies are using genetically engineered microbes to create fuel for the aviation and marine industries.[383] Based in the United States, biochemicals and biofuels company Gevo has developed aviation fuel that synthesizes hydrocarbons to create renewable jet fuels in various ways that the company describes as "alcohol-to-jet, oil-to-jet, syngas-to-jet, and sugar-to-jet."[384] It is also developing a fermentation

[378] *Sumitomo Chemical and Zymergen announce partnership to develop renewable specialty chemicals*, Sumitomo Chemical and Zymergen, April 17, 2019.
[379] Brenda Oppert and Lindsey Perkin, "RNAiSeq: How to see the big picture," *Frontiers in Microbiology*, November 14, 2019.
[380] Aggie Mika, "First RNAi insecticide approved," *The Scientist*, June 27, 2017.
[381] Jennifer Nyberg, *Sugar-based ethanol: International market profile*, FAO, 2005.
[382] *Bioethanol market 2018 global industry share, size, future demand, global research, top leading players, emerging trends, region by forecast to 2022*, Market Watch, June 25, 2019.
[383] Peggy Hollinger, "Greener biofuels battle for take-off to cut aviation emissions," *Financial Times*, March 30, 2020; Jonathan Saul, *Shipping companies, retailers look to develop cleaner marine biofuel*, Nasdaq, October 29, 2019; and Mike Kass et al., *Understanding the opportunities of biofuels for marine shipping*, Oak Ridge National Laboratory, December 2018.
[384] *Sustainable aviation fuel*, Gevo, December 2019.

process to produce isobutanol from corn-based fermentable sugar.[385] Algenol Biofuels has demonstrated the ability to produce ethanol using engineered algae. Norwegian cruise ship and ferry company Hurtigruten is planning to power its ships by processing fish waste from the fishing and animal-feed industries into an oil.[386]

Many of these technologies are in the early stage of development, and their economics remain challenging. Such innovations require high up-front capital investments, and it is difficult to reach sufficient scale in production to make the economics work. Many companies have tried and failed. One example is the bipartisan US government effort to make cellulosic ethanol from plants, a program that ran for 11 years. This resulted in increased production of this "second-generation" (2G) biofuel that uses not only the starch of the plant, but all of its biomass, making it a more efficient process and therefore less competitive with the food supply. However, by 2017, only 10 million gallons were produced, less than 0.1 percent of the target.[387] Given the relatively low cost and convenience of crude oil, more sustainable options will likely continue to face challenges in competing on economics alone, absent antipollution incentives. As a result, although this area appears promising, its potential remains relatively small based on current market factors in the timescale we have analyzed.

Extraction of energy sources and other raw materials

Extraction of raw materials, including oil, from the earth may be enhanced using genetically engineered microbes. Sequencing microorganisms could help determine an optimal oil drilling site; DNA testing of microbes from rock samples to help pinpoint areas with the biggest potential could shave costs by as much as 10 percent, some estimates suggest.[388] Microbial assessment and treatment can also reduce the impact of microbiologically influenced corrosion (as microorganisms adhere to the surfaces of metals and nonmetallic materials, forming a biofilm under which corrosion occurs) in oil extraction and transportation.[389] If this technology bears fruit, it could be applied to the extraction of gold and other metals, too. Microbial-enhanced oil recovery is another interesting area; this involves microbes designed to direct crude oil upward to the surface by breaking it down to reduce its viscosity.

Energy storage

Biological advances that improve the storage of energy have been a topic of broad interest in academic research over the past few decades, but practical applications have been limited. Efforts have focused on two main areas with potential to disrupt the energy landscape—biobatteries and the use of engineered microorganisms to create advanced electrodes for next-generation batteries.

Biobatteries are essentially fuel cells that use enzymes to produce electricity from sugar. Interest is growing in their ability to convert easily storable fuel found in everyday sugar into electricity and the potential energy density this would provide. At 596 ampere hours per kilogram, the density of sugar would be ten times that of current lithium-ion batteries. Additional benefits would include low fuel costs, portability to remote settings, and sustainability. However, recent advances have not led to any commercialized, cost-competitive solutions, and practical uses are unlikely to emerge in the near future. Barriers that need to be overcome include the short shelf life of the microorganisms and falling efficiencies as solutions are scaled up.[390]

[385] *From the sugar platform to biofuels and biochemicals: Final report for the European Commission Directorate-General Energy*, European Commission, April 2015.
[386] Terri Colby, "Hurtigruten announces it will fuel cruise ships with dead fish," *Forbes*, November 19, 2018.
[387] John Fialka, "How a government program to get ethanol from plants failed," *Scientific American*, July 16, 2018; and Robert Rapier, "Cellulosic ethanol falling far short of the hype," *Forbes*, February 11, 2018.
[388] Ernest Scheyder, "The DNA of oil wells, U.S. shale enlists genetics to boost output," Reuters, March 28, 2017.
[389] Judit Telegdi, Abdul Shaban, and Laszlo Trif, *Trends in oil and gas corrosion research and technologies*, Woodhead Publishing Series in Energy, 2017.
[390] Zhiguang Zhu et al., "A high-energy-density sugar biobattery based on a synthetic enzymatic pathway," *Nature Communications*, January 21, 2014.

Potentially more applicable in the near term is the use of engineered microorganisms to create advanced electrodes in next-generation batteries. Broadly, microorganisms, including bacteria, fungi, and viruses, have the potential to develop high-performance electrodes because they are able to reproduce quickly and are susceptible to gene modification, biomineralization, and self-assembly. Specifically, lithium-air devices have received both academic and commercial attention as a potential next-generation battery technology, but the need for advanced electrodes remains. Synthesis of these electrodes using microorganisms has been demonstrated to be possible in a process directed by certain types of virus.[391] As industrial interest in these types of high-performance electrode material production increases, microorganisms show potential to provide a low-cost synthesis that could accelerate developments in energy storage.

[391] Dahyun Oh et al., "M13 virus-directed synthesis of nanostructured metal oxides for lithium-oxygen batteries," *Nano Letters*, August 2014, Volume 14, Issue 8.

Tubular bioreactors filled with green algae fixing CO_2
© Santiago Urquijo/Moment/Getty Images

6.5. Sustainability and other applications

Bio innovations within the arenas of biomolecules and biosystems may apply to other areas beyond the "big four" of healthcare; agriculture; consumer products and services; and materials, chemicals, and energy. Here, we focus on several nascent applications, including developments that could undo environmental harm, further space exploration, or be used in education and security.

These potential applications—and eventual impact—are highly uncertain. They probably will unfold only in the longer term, and they come with sometimes significant risks. For all of these caveats, we have nonetheless attempted to size the potential impact over the next ten to 20 years, based on the limited use cases we have compiled. Excluding space exploration, for which we do not expect applications to become commercially available before 2050, we estimate the potential direct annual impact of these other applications, taken together, at roughly $25 billion to $45 billion globally.

Biosequestration and bioremediation could help address environmental challenges

The world faces interrelated environmental challenges. The climate is changing. The planet's average temperature has risen 1.1 degrees Celsius due to man-made GHG emissions in the past century, and average temperatures are set to rise further.[392] As they do, climate science finds that acute hazards such as heat waves and floods grow in frequency and severity, and chronic hazards, such as drought and rising sea levels, intensify.[393] The WHO estimates that an estimated 4.2 million premature deaths globally are linked to ambient (outdoor) air pollution.[394] Biodiversity is vital, making production systems and livelihoods resilient to shocks and stresses, including climate change. The United Nations reports "unprecedented" loss of species, with extinction threatening about one million of the planet's estimated eight million plant and animal species, many within decades. In addition, the FAO says that biodiversity in food and agriculture is in decline.[395]

Throughout this report, we discuss uses of omics and molecular technologies that have the potential to indirectly reduce carbon emissions and environmental degradation through less environmentally stressful, biological means of producing materials or conducting agriculture. Here we discuss work under way to directly monitor, and reverse, harm already done to the environment. We look at three categories of potential applications of omics and molecular technologies: biosequestration, bioremediation, and monitoring for signs of environmental and ecological damage. We have estimated the potential of the first two, which our analysis suggests could have an impact of $15 billion to $30 billion over the next ten to 20 years. It is important to note that the technologies are at an early stage, and taking these applications from the lab to large-scale use—for instance, on cropland around the world—will hinge on more than scientific advances, including making the economics work and addressing the profound risks that come with these transformative technologies, as discussed in chapter 3 of this report.

[392] Nathan J. L. Lenssen et al., "Improvements in the GISTEMP Uncertainty Model," *Journal of Geophysical Research, Atmospheres*, May 23, 2019, Volume 124, Issue 2.
[393] *Climate risk and response: Physical hazards and socioeconomic impacts*, McKinsey Global Institute, January 2020.
[394] *Ambient air pollution: Health impacts*, World Health Organization.
[395] The report assesses biodiversity for food and agriculture and its worldwide management, drawing on 91 country reports and 27 reports from international organizations. See *The state of the world's biodiversity for food and agriculture*, FAO Commission on Genetic Resources for Food and Agriculture, Assessments, 2019.

Biosequestration

GHG emissions, including those from changes in land use, reached a record high of 75.9 gigatonnes of CO_2 equivalent ($GtCO_2$) in 2018.[396] Stabilizing the climate will require a transition to net zero carbon emissions, including at-scale removal of CO_2 from the atmosphere.

Biosequestration is the term for biological means of taking CO_2 out of the atmosphere.[397] Over the long term, the full adoption of omics and molecular technologies in biosequestration could potentially capture about 1.2 to 1.4 $GtCO_2$. In this section, we look at three agents of carbon biosequestration—plants, algae, and bacteria—whose carbon sequestration efficiency could be potentially enhanced by omics and molecular technologies:

— **Plants.** Even with extremely optimistic assumptions about new carbon dioxide removal approaches, there would still need to be very large-scale nature-based CO_2 removal.[398] Plants have been performing this role for millions of years, but the loss of forested habitat has limited the scale of nature-based carbon capture. To meet the challenge of keeping global warming to a maximum of 1.5 degrees Celsius, as set out by the Intergovernmental Panel on Climate Change, reforestation on a massive scale would be needed between now and 2030.[399] An area at least twice the size of Iceland—and potentially as large as the United Kingdom—would need to be reforested annually. Omics and molecular technologies could supplement the effort. Genetically engineered plants can potentially store more CO_2 for longer periods than their natural counterparts. Plants normally take in CO_2 from the atmosphere and store carbon in their roots. The Harnessing Plant Initiative at the Salk Institute is using gene editing to create plants with deeper and more extensive root systems that can store more carbon than typical plants. These roots are also engineered to produce more suberin or cork, a naturally occurring carbon-rich substance found in roots that absorbs carbon, resists decomposition (which releases carbon back into the atmosphere), may enrich soil, and helps plants resist stress. When these plants die, they release less carbon back into the atmosphere than conventional plants. If about 5 percent of the world's cropland—or about the land area planted with genetically engineered soybeans in the United States in 2018—were to be planted with crops with the traits being explored, as much as 0.8 gigatonnes of CO_2 equivalent could be captured every year, according to the Salk Institute.[400] As a comparison, the total CO_2 emissions of the global airline industry were about 0.9 gigatonnes in 2018.[401]

  Widespread adoption of genetically engineered plants involves challenges, uncertainties, and risks, however. Thus far, most genetically engineered plants have been developed in the lab and have yet to be tested in major crops in the field. Additionally, regulatory barriers could impede their adoption. The Court of Justice of the European Union ruled in July 2018 that gene-edited crops should be subject to the same stringent regulations as conventional GM organisms.[402] As with all bio innovations, the economics of these plants would need to work to persuade farmers to adopt them. Overall, it is likely that any shift to genetically engineered plants for the purposes of carbon sequestration will not happen quickly.

396 Total GHG emissions, including from land use, land-use change, and forestry, were 75.9 $GtCO_2e$ in 2018, according to the UN's *Emissions gap report 2019*. All GHG emission figures are expressed using 20-year global warming potential (GWP20).

397 Avnish Nitin Mistry et al., "A review on biological systems for CO_2 sequestration: Organisms and their pathways," *Environmental Progress and Sustainable Energy*, October 2018, Volume 38, Issue 1; and *Carbon cycling and biosequestration: Integrating biology and climate through systems science*, US Department of Energy, December 2008

398 For more on plant biosequestration, see Christer Jansson et al., "Phytosequestration: Carbon biosequestration by plants and the prospects of genetic engineering," *BioScience*, October 2010, Volume 60, Number 9.

399 *Climate change 2013: The physical science basis*, Intergovernmental Panel on Climate Change, 2013.

400 Leslie Hook, "Could a superplant save the planet?," *Financial Times*, January 31, 2019.

401 *ICAO global environmental trends – present and future aircraft noise and emissions*, International Civil Aviation Organization working paper number 54, May 7, 2019.

402 Ewen Callaway, "CRISPR plants now subject to tough GM laws in European Union," *Nature*, July 25, 2018.

— **Algae.** Algae, present throughout the biosphere but particularly in marine and freshwater environments, are among the most efficient organisms for carbon sequestration and photosynthesis; they are generally considered photosynthetically more efficient than terrestrial plants.[403] Potential uses of microalgal biomass after sequestration could include biodiesel production, fodder for livestock, and production of colorants and vitamins. Using microalgae to sequester carbon has a number of advantages. They do not require arable land and are capable of surviving well in places that other crop plants cannot inhabit, such as saline-alkaline water, land, and wastewater. Because microalgae are tiny, they can be placed virtually anywhere, including cities. They also grow rapidly. Most important, their CO_2 fixation efficiency has been estimated at ten to 50 times higher than that of terrestrial plants.[404]

  Editing tools, including CRISPR–Cas9 and TALEN, are already being used to alter microalgal genes; tools that interfere with genes, including miRNA and siRNA, are also being explored.[405] In 2017, a team of scientists genetically engineered one type of microalgae and increased its capacity to perform photosynthesis by 1.2 times.[406] Several companies, including Fermentalg and UEZ, are working on commercializing microalgae technology.[407] They have designed genetically engineered algae capable of capturing CO_2 and transforming it into biofuels. Despite enormous potential and some innovation among startups, microalgae-based biosequestration has not reached significant scale, and there are hurdles both upstream and downstream to scaling up and commercialization. For example, algae cultivation based on the aqua-suspend method has low biomass productivity.[408] It requires a large amount of water and energy, which makes scaling up challenging.[409]

— **Bacteria.** Many bacteria have the ability to sequester atmospheric CO_2.[410] They have a number of advantages, including the fact that they can be produced rapidly, are proficient at fixing carbon, have a high capacity to produce a wide range of additive (biodegradable) products, including biofuels and bioplastics, and are relatively easy to genetically engineer. Scientists have reengineered one bacterium that eats a diet of simple sugars into one that builds its cells by absorbing CO_2. For now, commercial applications are limited and technical challenges remain (in improving carbon fixation, for instance), but advances could perhaps lead to the development of engineered microbes that extract CO_2 out of the air and turn it into medicines and other high-value compounds.[411]

Bioremediation

Bioremediation is a process that aims to remove toxins from the environment—soil, water, and the atmosphere—by using biological organisms, including plants, algae, fungi, and microorganisms. Today, some scientists are testing genetic engineering in bioremediation to create a sustainable, potentially cost-effective system to remove inorganic and organic compounds that may be harmful to the environment.

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403 Algae exist in many forms including large macroalgae and smaller microalgae. See Avnish Nitin Mistry et al., "A review on biological systems for CO_2 sequestration: Organisms and their pathways," *Environmental Progress and Sustainable Energy*, October 2018, Volume 38, Issue 1.

404 Ibid.

405 I-Son Ng et al., "Recent developments on genetic engineering of microalgae for biofuels and bio-based chemicals," *Biotechnology Journal*, October 2017, Volume 12, Issue 10; and Sheeja Jagadevan et al., "Recent developments in synthetic biology and metabolic engineering in microalgae towards biofuel production," *Biotechnology for Biofuels,* June 2018, Volume 11, Number 185.

406 Bo Yang et al., "Genetic engineering of the Calvin cycle toward enhanced photosynthetic CO_2 fixation in microalgae," *Biotechnology for Biofuels*, October 2017, Volume 10.

407 *Transforming CO_2 into green energy*, SUEZ and Fermentalg, September 25, 2017.

408 Net increase in plant dry matter per unit of light intercepted.

409 Jyoti Singh and Dolly Wattal Dhar, "Overview of carbon capture technology: Microalgal biorefinery concept and state-of-the-art," *Frontiers in Marine Science*, February 2019.

410 Avnish Nitin Mistry et al., "A review on biological systems for CO_2 sequestration: Organisms and their pathways," *Environmental Progress and Sustainable Energy*, October 2018, Volume 38, Issue 1.

411 Robert F. Service, "This microbe no longer needs to eat food to grow, thanks to a bit of genetic engineering," *Science*, November 27, 2019.

One example is genetically engineered microbes that can be used to break down waste and toxins, and could, for instance, be used to reclaim mines.[412] Some headway is being made in using microbes to recycle textiles. Processing cotton, for instance, is highly resource-intensive, and dwindling resources are constraining the production of petroleum-based fibers such as acrylic, polyester, nylon, and spandex. There is a great deal of waste, with worn-out and damaged clothes often thrown away rather than repaired.[413] Less than 1 percent of the material used to produce clothing is recycled into new clothing, representing a loss of more than $100 billion a year.[414] Los Angeles–based Ambercycle has genetically engineered microbes to digest polymers from old textiles and convert them into polymers that can be spun into yarns. Engineered microbes can also assist in the treatment of wastewater. In the United States, drinking water and wastewater systems account for between 3 and 4 percent of energy use and emit more than 45 million tons of GHG a year.[415] Microbes—also known as microbial fuel cells—can convert sewage into clean water as well as generate the electricity that powers the process.[416]

As is the case with biosequestration, most bioremediation technologies are still being tested in the lab, are not yet scaled and commercialized, and potentially will need to surmount public and regulatory misgivings that could surface with all types of genetic engineering.

Monitor the environment

Genomics can be used to monitor genetic biodiversity, carry out biosurveillance of invasive species, identify environmental issues such as contamination and pollution, and potentially do so more quickly and effectively than is currently possible. For example, genetic tools can be used in the conservation of endangered species by improving the monitoring of genetic biodiversity and using genetic information as evidence in court in poaching cases.[417] Genomic tools can be used to better understand and potentially manage invasive species, including by offering insights into mechanisms of invasions and the role of genetic variation.[418] Additionally, instead of using animals, genomics-based animal-free systems have been used for better, faster, and cheaper toxicity testing of thousands of chemicals that affect the health of ecosystems and the animals within them in a range of contexts, from oil and chemical spills to everyday pharmaceutical and cosmetic products.[419]

Defense and security also lend themselves to some biological applications, although the risks could outweigh the benefits

An emerging set of applications that apply omics or molecular technologies could potentially be used in the area of defense and security. These applications are all nascent—and fraught with risks and ethical considerations. Society and governments will need to heavily weigh the associated risks and the potential unintended consequences. While the applications have

412 Lina Liu et al., "Mitigation of environmental pollution by genetically engineered bacteria—current challenges and future perspectives," *Science of the Total Environment*, June 2019, Volume 667; and Cassiana S. De Sousa et al., "Microbial omics: Applications in biotechnology," in *Omics Technologies and Bio-Engineering: Towards Improving Quality of Life,* Volume 2, Debmalya Barh and Vasco Azevedo, eds., London, UK: Academic Press, 2017.

413 *Fashion forward: How tech is targeting waste and pollution in the $2.4T fashion industry*, CBInsights, June 2019.

414 *A new textiles economy: Redesigning fashion's future*, Ellen MacArthur Foundation and Circular Fibres Initiative, 2017; and *Is apparel manufacturing coming home? Nearshoring, automation, and sustainability – establishing a demand-focused apparel value chain*, McKinsey & Company, October 2018.

415 *Energy efficiency in water and wastewater facilities: A guide to developing and implementing greenhouse gas reduction programs*, Local Government Climate and Energy Strategy Guides, US Environmental Protection Agency, 2013; and Sally Adee, "Bacteria made to turn sewage into clean water—and electricity," *New Scientist*, July 27, 2016.

416 Zhuwei Du, Haoran Li, and Tingyue Gu, "A state of the art review on microbial fuel cells: A promising technology for wastewater treatment and bioenergy," *Biotechnology Advances*, 2007, Volume 25; and Bruce E. Logan et al., "Microbial fuel cells: Methodology and technology," *Environmental Science & Technology*, July 2006, Volume 40, Issue 17.

417 Megan A. Supple and Beth Shapiro, "Conservation of biodiversity in the genomics era," *Genome Biology*, 2018, Volume 19, Number 131; Priscila F. M. Conçalves et al., "DNA barcoding identifies illegal parrot trade," *Journal of Heredity*, 2015, Volume 106, Supplement 1; and R. Lorenzini, "DNA forensics and the poaching of wildlife in Italy: A case study," *Forensic Science International*, October 2005, Volume 153.

418 Steven L. Chown et al., "Biological invasions, climate change and genomics," *Evolutionary Applications*, January 2015, Volume 8, Issue 1; Carol Eunmi Lee, "Evolutionary genetics of invasive species," *Trends in Ecology & Evolution*, August 2002, Volume 17, Issue 8; and Ningning Wu et al., "Fall webworm genomes yield insights into rapid adaptation of invasive species," *Nature Ecology & Evolution*, December 2018, Volume 3.

419 Brandon D. Gaytán and Chris D. Vulpe, "Functional toxicology: Tools to advance the future of toxicity testing," *Frontiers in Genetics*, May 2014; and *NIH collaborates with EPA to improve the safety testing of chemicals—new strategy aims to reduce reliance on animal testing*, US Environmental Protection Agency, February 15, 2008.

potential benefits or may mark improvements on existing substitutes, their use could erode public trust or increase geopolitical risk.

Some applications are already being used in security and law enforcement, such as DNA sequencing for policing—which is raising significant privacy concerns. It may be possible in the future to use DNA testing as biometric verification to open bank accounts, to prevent credit card fraud, and even to use security lines at airports. It is unlikely that the cost and speed of DNA testing will be low enough within the time frame of 30 years to replace the next best alternative, namely fingerprint scanning, which is instantaneous and inexpensive. As noted in the earlier section on consumer applications, the use of DNA testing for these purposes carries significant privacy concerns (and worries about false positives and negatives).

In defense, the applications surveyed but not sized include improving the effectiveness of armed forces through genetic engineering, and developing offensive or defensive bioweapons. Intense resistance to any movement toward genetically modifying troops is likely, especially in democratic countries. However, if the field benefits appear to be sufficiently compelling, some countries may try to adopt such applications, potentially setting off a new arms race.

Bio innovations may affect education and talent development, but scientific challenges and ethical concerns need to be considered

Bio innovation could be applied to education and the development of talent. In education, potential applications include personalizing learning based on genetic profiles, if omics and molecular technologies enable us to make a more nuanced understanding of what each child needs in order to learn most effectively by analyzing DNA variants such as memory, reaction time, and learning ability. It may be possible to use genetic profiling to detect students who are more prone to dropping out of school and channel more resources toward them to prevent it.[420] It may also be possible to actively identify learning disorders that have links to genetic profiles (such as ADHD and dyslexia, as proxies) early, and for appropriate therapeutic interventions to be taken.[421] In the case of training, genetic profiling could be used to counsel individuals toward particular career paths based on predicted talents. Athletes could be selected based on their genetics, which is already happening in Australia and China and could spread to other countries.[422] The direct impact could be between roughly $3 billion and $5 billion over the next ten to 20 years from premium learning programs tailored based on genomes, but most applications might not have impact before 2050.

Ethical concerns cannot be discounted. The morality of determining (or even suggesting) educational or career pathways based upon genetics is fraught, based on today's evidence and knowledge. It is already known that teachers' expectations have a strong impact on actual outcomes for their students. Therefore, a teacher even suggesting that some students are less likely to succeed and could, for instance, be better suited for a vocational pathway could become a self-fulfilling prophecy. Furthermore, predetermining children's educational paths based on their genetics could reinforce inequality if these tools are open only to the wealthy or to citizens of countries that take a permissive view of regulation in this area. For these reasons, biological advances in this field should be treated with the utmost caution.

[420] Aysu Okbay et al., "Genome-wide association study identifies 74 loci associated with educational attainment," *Nature*, May 11, 2016, Volume 533, Issue 7604.

[421] Anita Thapar and Evangelia Stergiakouli, "An overview on the genetics of ADHD," *Xin Li Xue Bao (Acta Psychologica Sinica)*, October 2008, Volume 40, Issue 10.

[422] "Talent identification and performance genes," in *Essentially yours: The protection of human genetic information in Australia (ALRC Report 96)*, Australian Government and Australian Law Reform Commission, 2003; Stephen Chen, "Gattacca by 2022? China to select Winter Olympics athletes by their genes," *South China Morning Post*, August 31, 2018; and Ysabel Jacob et al., "The potential role of genetic markers in talent identification and athlete assessment in elite sport," *Sports*, September 2018, Volume 6, Issue 3.

Space exploration is another area where there is interest in using omics and molecular technologies

Bio innovations could be used to improve space exploration. The use of omics and molecular technologies in the space industry is fascinating but, at this point, highly speculative. For this reason, we have not estimated what the potential impact might be. In any case, any impact could emerge beyond 2050. It is possible that omics and molecular technologies could eventually be used to develop habitats in space, or to study aging in space in the near future to gain insights into how human beings age on Earth:

— **Space habitat.** It may in future be possible to use genetically engineered microbes to terraform other planets, such as Mars.[423] Biofoundries could be established that test millions of DNA designs in parallel to identify organisms that could be most suitable for the environment or most useful as a food source on Mars—if there is one day a migration there for whatever reason.[424] It may also be possible to construct Martian habitats more efficiently and in a more environmentally responsible way using mushrooms, which can be genetically engineered to secrete certain substances like bioplastics.[425] In the nearer term, short of terraforming another planet, omics and molecular technologies could usefully enable more sustainable generation of oxygen and food sources in controlled environments.

— **Space-based health.** More probable in a reasonable time frame are applications of space-based health. Astronauts have been conducting space travel since 1961, and bio innovations may be helpful in several areas. Medical advances can inform optimized space health and survival, and conversely, medical research in space can yield findings that would otherwise have been difficult or impossible to identify on Earth. It may be possible to tailor pharmacology to the personal genomic profile of astronauts to enable them to stay healthy in space. NASA is currently conducting research on aging in space (since living beings age faster in space) in order to study the physiology of aging and disease progression on Earth.[426] NASA followed twin astronauts on a year-long mission on the International Space Station to explore molecular and physiological traits that may be affected by spending prolonged periods in space. The NASA Twins Study found that the length of telomeres, which are important to cell division, changed substantially during space flight and then again on return to Earth. The study also found changes in DNA methylation in immune cells as well as cardiovascular and cognitive effects.[427] NASA's Artemis program is looking at how partial gravity affects the body compared with microgravity, science that could potentially be applied to future visits to Mars. Another potential area for study is how to protect human beings from radiation in space.[428] As far off as they may seem, there could be uses for such technological approaches in improving health—of people on Earth and in space—resulting in downstream impacts on the pharmaceutical industry.

[423] William Herkewitz, "Here's how we'll terraform Mars with microbes," *Popular Mechanics*, May 7, 2015.
[424] Briardo Llorente, *How to grow crops on Mars if we are to live on the red planet*, Synbiobeta, July 26, 2018. For more, see *BetaSpace*, Synbiobeta, 2019.
[425] Lynn Rothschild, *Myco-architecture off planet: Growing surface structures at destination*, NASA TV, March 30, 2018; and Fiona Mischel, *Moving to Mars? Biomaterials point the way*, Synbiobeta, November 26, 2018.
[426] *Aging faster in space to age better on earth*, NASA, January 2019.
[427] Frances E. Garrett-Bakelman et al., "The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight," *Science*, April 2019, Volume 364, Issue 6436.
[428] *Real Martians: How to protect astronauts from space radiation on Mars*, NASA TV, September 30, 2015.

Paraplegic learns to walk again with electrically powered exoskeleton at ETH Zurich research lab
© EThamPhoto/The Image Bank Unreleased/Getty Images

6.6. Biomachine interfaces

Over the past decade, more complex and advanced algorithms and systems have made the development of true biomachine interfaces possible. Refinements to methods for detecting brain signals are creating higher-quality, more detailed data. More advanced analytics processing, supported by ever more sophisticated AI and machine learning, enables better interpretation of signals with the future promise of identifying specific phrases or conscious commands from users. Other technical improvements are enabling the translation of brain data into action at a greater level of precision; an example is the development of prosthetic hands that are capable of detailed motions. The potential exists to create stable systems in which computers and AI augment the capabilities of the brain. The scope of applications for biomachine interfaces is very broad.

Biomachine interfaces create impact in several domains, including neuroprosthetics that restore hearing or vision in human health and performance, and headbands for monitoring stress levels from electric signals in consumer products and services. The timing of adoption of applications will vary. The most advanced biomachine interfaces are currently in healthcare. Many of them are not likely to be commercialized within the next ten years (Exhibit 25).

Exhibit 25

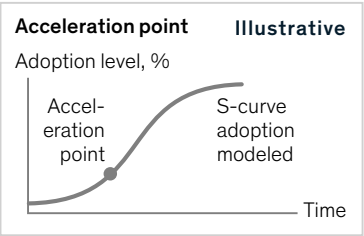
For applications in biomachine interfaces, timing of adoption varies.

Example use cases

Not exhaustive

Estimated time horizon of acceleration point of use cases in biomachine interfaces
The acceleration point is when adoption starts to experience rapid growth[1]

Existing Before 2020	**Short term** 2020–30	**Medium term** 2030–40	**Long term** Beyond 2040
Provide basic gaming control via brain monitoring headsets Deep brain stimulation for Parkinson's and essential tremor Neuroprosthetics for hearing (cochlear implants) Brain activity monitoring to diagnose disease (eg, EEG)	Neuroprosthetics for sight (bionic vision) Deep brain stimulation for Alzheimer's, depression, anxiety Neuropriming for athletic performance Neuroprosthetics for motor control (implant or external headset) of human or robotic limb Mental state monitoring via measured brain waves	Neuroergonomics to improve workplace design (eg, reduce stress levels in cockpit) Direct brain-to-device communication for paralyzed patients unable to communicate	Interpret pet's emotions through measured brain waves Enhance sensory perception for consumer use Computational augmentation of the brain (link directly to computer chip) Control consumer electronics via headsets reading brain signals (eg, smartphone)



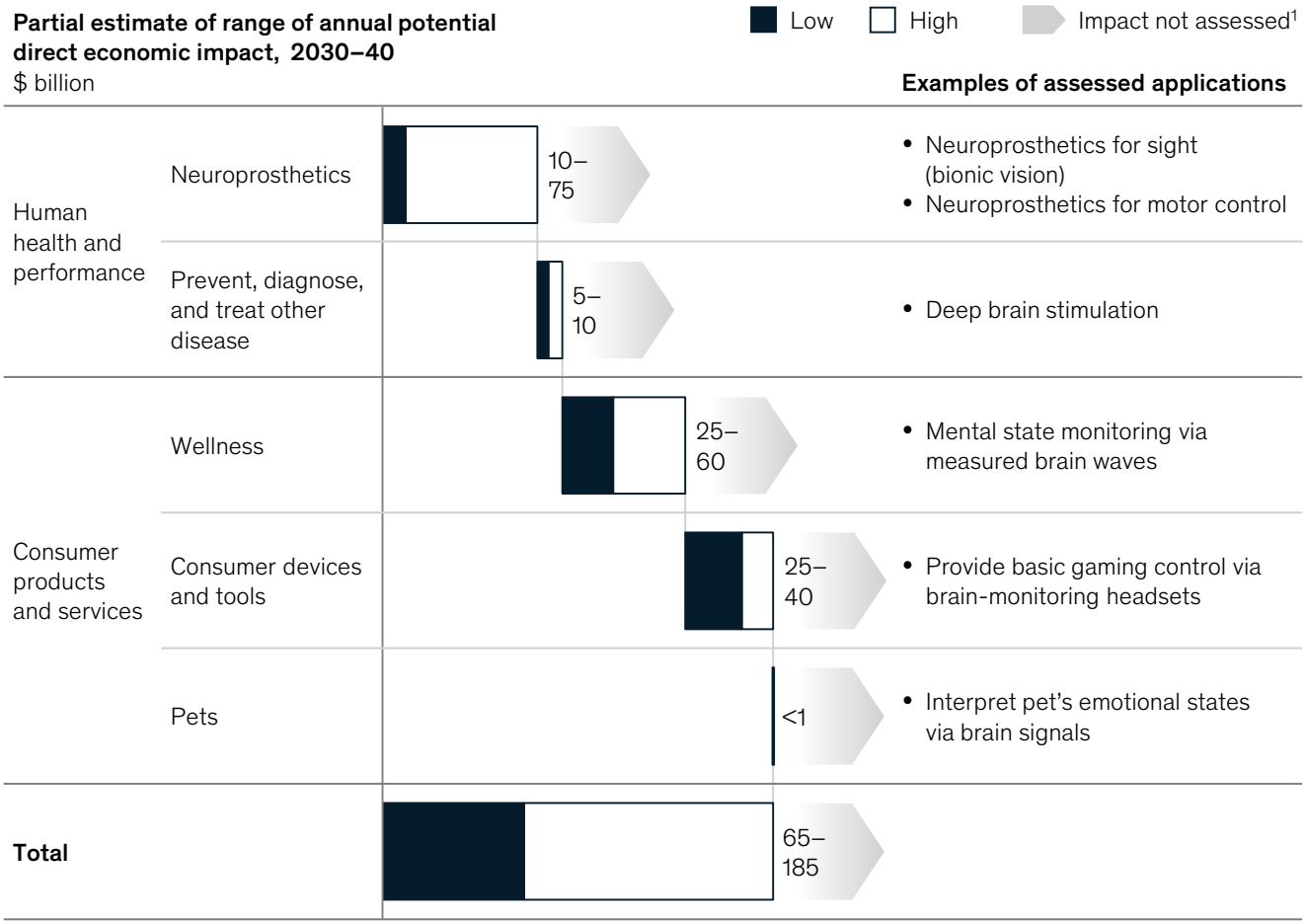
1. The point at which adoption accelerates. We characterize this as the max of the second derivative of the adoption curve—see our technical appendix for more detail. Adoption level and timing for each use case depend on many variables, including commercial availability, regulation, and public acceptance. These estimates are not fully risk- or probability-adjusted.

Source: McKinsey Global Institute analysis

In the next ten to 20 years, the direct annual impact could potentially range between about $70 billion and $200 billion globally, or 5 percent of the total for the use cases assessed (Exhibit 26).

Exhibit 26

Annual impact of $70 billion to $200 billion could be created in biomachine interfaces in the next ten to 20 years.



1. Including, but not limited to, indirect impacts from assessed applications and impacts from unassessed applications.
Note: Figures may not sum to 100% because of rounding. These impact estimates are not comprehensive; they include only potential direct impact of the visible pipeline of applications identified and assessed. Estimates do not represent GDP or market size (revenue), but direct economic impact; broader knock-on economic effects are not included. Estimates are relative to the 2020 economy; they do not include changes in variables such as demographics and inflation.
Source: McKinsey Global Institute analysis

Biomachine interfaces could have many applications in healthcare

We examine two main groups of applications in healthcare: neuroprosthetics involving establishing stable systems between a machine and the patient's nervous system to replace or restore neural inputs and outputs, and other treatments or diagnostic technologies that stimulate the brain or interpret its signals.

Neuroprosthetics

Neuroprosthetics link the human nervous system to computers, thereby providing control of prosthetic limbs and restoring lost sensory function.[429] Already well established are cochlear implants for hearing, which have been widely available since the late 1980s. Continuing refinements in these technologies are likely. They include more sophisticated analytics for auditory signal processing to enable improved recognition of sounds and language. Improved devices that are easier to implant and use are another possibility.[430] Substantial developments

[429] Eric C. Leuthardt, Jarod L. Roland, and Wilson Z. Ray, "Neuroprosthetics," *The Scientist*, November 2014.
[430] Teresa A. Zwolan, "Recent advances in cochlear implants," *Contemporary Issues in Communication Science and Disorders*, Fall 2008, Volume 35.

have been made in bionic vision over the past 20 years. For instance, SecondSight has developed a retinal implant called the Argus II that has restored notable functions to patients, including the ability to distinguish shapes, sense light, and even read print at a basic level in some cases.[431] The EU approved Argus II in 2011.[432] The United States approved it two years later.[433] This technology is relatively new, so there should be refinements in the quality of vision enabled and broader distribution to patients.

Neuroprosthetics for motor control for people who have lost limbs or who have intact limbs but have lost control due to nervous system damage have made significant progress (Exhibit 27). In the past, the first group had no control over a prosthetic. But now patients who still have nervous system connections are able to use myoelectric devices that respond to electrical signals from muscles.[434] One such device is the Hero Arm from Open Bionics.[435] Now, researchers are developing neuroprosthetic limbs that receive signals from a surgically implanted chip in the patient's brain. A team from the University of Chicago now has funding to develop these devices.[436] In addition, advanced motor-control neuroprosthetics are being developed that feed information directly from prostheses to the brain, creating a sense of touch that better enables control of motion.[437] Scientists at ETH Zurich have created sensors in bionic feet that send signals back to the tibial nerve in the leg, enabling patients to feel their prosthetic feet in real time.[438]

There have been large advances in prostheses for paraplegic patients who need to be able to sense brain signals directly that can be transmitted to their muscles. The MoreGrasp device is a headset with external electrodes that interprets brain signals.[439] Other devices are implanted in the brain. Scientists demonstrated this approach in experiments in 2015 using two rhesus monkeys that had suffered nerve damage leading to the loss of control in one leg. Chips were implanted in their skulls that were able to translate motor cortex signals into electrical impulses sent to the legs. Both monkeys recovered the ability to walk within two weeks, indicating the potential for this approach to be used in human patients.[440] Another application is the brain-controlled exoskeleton operated through a headset or an implant. One team developed an exoskeleton that could be controlled by a headset, and the paraplegic patient recovered enough motion control to perform the symbolic kickoff at the 2014 World Cup.[441]

Researchers are even now exploring the possibility of directly translating language from patients' brains to computers—brain-to-device communications—using either a surgically inserted neuroprosthetic device or a headband. This technique could have significant benefits for patients who are suffering from "locked-in syndrome" paraplegia and have lost the ability to control their vocal cords.[442] Today, such patients either are unable to communicate or have to use technologies such as eye-tracking devices that painstakingly spell out words letter by letter.[443] In 2019, researchers at the University of California, San Francisco, reported using neuroprosthetics to receive and interpret brain signals in the part of the motor cortex that controls the larynx. It was possible to identify the words in 80 percent of synthesized sentences.

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431 Duncan Graham-Rowe, "Visions of the future," *Wired*, August 6, 2010.
432 Duncan Graham-Rowe, "A bionic eye comes to market," *MIT Technology Review*, March 7, 2011.
433 Julie Steenhuysen, "FDA approves first retinal implant for rare eye disease," Reuters, February 14, 2013.
434 Chris Woodford, *Prosthetic limbs*, Explain That Stuff, February 25, 2019.
435 Mike Butcher, *Open Bionics closed $5.9m Series A for its affordable and cool bionic limbs*, TechCrunch, January 14, 2019.
436 Matt Wood, *Neuroscience researchers receive $3.4 million NIH grant to develop brain-controlled prosthetic limbs*, UChicago Medicine, October 16, 2018.
437 We sized the potential use of neuroprosthetics for limb loss, which could include some that have haptic feedback; we did not size haptic feedback separately because its most common use cases are in limb loss. Haptic feedback is the use of touch to communicate with users.
438 Judy George, *Neuroprosthetic leg recreates foot, knee sensations*, Medpage Today, October 2, 2019.
439 *Advances in motor neuroprosthetics improve mobility in tetraplegics*, Bitbrain, October 16, 2018.
440 Glenn McDonald, *Brain implant could help paraplegics walk again*, Seeker, September 11, 2016.
441 Alejandra Martins and Paul Rincon, "Paraplegic in robotic suit kicks off World Cup," BBC, June 12, 2014.
442 Conditions that cause locked-in syndrome can include severe motor neuron disease, stroke, and traumatic brain injuries.
443 *Locked-in syndrome patients given new revolutionary AI-powered device*, Health Europa, August 20, 2018.

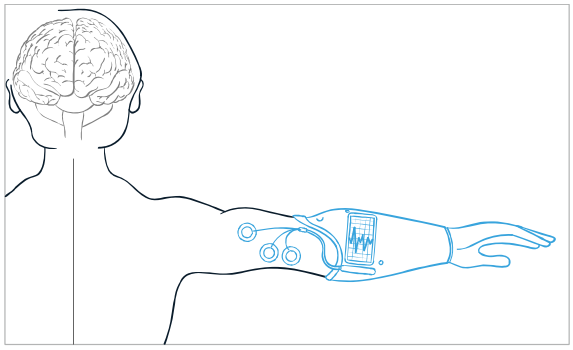
Beyond neuroprosthetics, biomachine interface innovations can be used to diagnose and treat a variety of diseases. Electroencephalogram (EEG) signals have been used in conjunction with behavioral tests to assess whether patients have Alzheimer's and Parkinson's disease.[444] Other commonly used measures for understanding brain activity in order to diagnose disease include CT scans, MRIs, PETs, and SPECTs.[445] And innovative new biomachine interface–based healthcare approaches are now emerging such as deep brain stimulation.

Exhibit 27

Neuroprosthetics can restore motor control for different conditions.

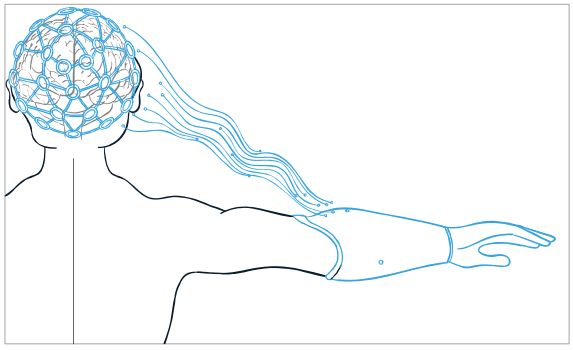
Patients with physical limb loss

Myoelectric devices



Read electric signals from muscle of remaining limb to control prosthetic limb

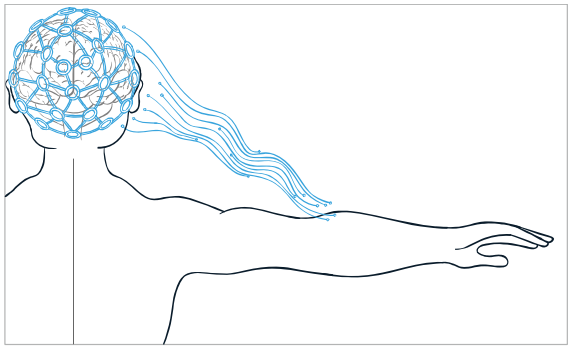
Neural implant or headband devices



Read signals directly from brain, through surgically implanted chip or through headband, to control artificial limb

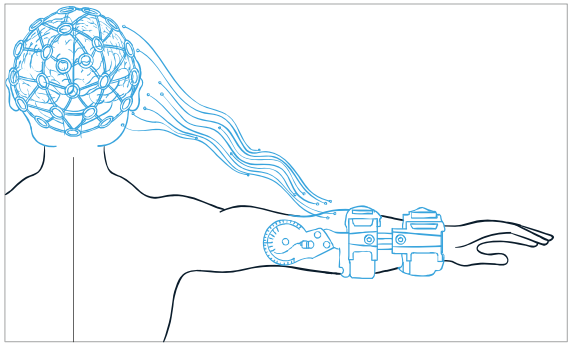
Patients with limb paralysis (nervous system damage)

Muscle stimulation



Read signals directly from brain, through surgically implanted chip or through headband, and convert signals to electric stimulation of muscles to control existing limb

Exoskeletons



Read electric signals directly from brain, through surgically implanted chip or through headband, to control external exoskeletal brace

Source: McKinsey Global Institute analysis

[444] EEG is short for electroencephalogram, a technique that records brain wave patterns. It works by attaching small metal discs to the scalp to measure electrical activity.
[445] *Neurological diagnostic tests and procedures fact sheet*, National Institute of Neurological Disorders and Stroke.

Deep brain stimulation

DBS uses a device that sends pulses of electric current to help mitigate some of the effects of neurological diseases.[446] The technology was approved by the FDA in the United States in 1997 for treating essential tremor often observed in Parkinson's, Parkinson's itself in 2002, and dystonia in 2003.[447] Research is ongoing into whether DBS can be applied to patients with Alzheimer's, depression, and anxiety, conditions for which DBS has not yet been approved.[448]

Mental state monitoring as an aid to therapy

In the future, more advanced brain signal-reading headsets or machines may emerge that can "read" patients' emotional state and therefore be a useful aid in therapy.[449] In 2013, researchers at Carnegie Mellon University were able to use functional magnetic resonance imaging (fMRI) and a machine learning algorithm to calibrate a machine that recognizes the emotions test subjects were experiencing with reasonable accuracy.[450] If this technique is refined, there is potential to use it to assist in therapy sessions.

Biomachine interfaces have consumer applications from wellness to advanced gaming devices

A number of biomachine interface prototypes for consumer applications have emerged, generating intense interest in the prospect of brain control. We highlight applications in wellness, consumer devices, and pets and pet care.

Wellness

Consumer interest in health wearables such as stress-monitoring headbands is growing. One of the earliest available consumer biomachine interfaces that interpreted EEG signals was the Muse headband, which began development in 2003 and was released commercially in 2014.[451] A team of Canadian neuroscientists spent a week in the Mars Habitat at the Hawaii Space Exploration Analog and Simulation to explore options for monitoring the brain health of astronauts on future Mars missions in real time, and used the Muse headband.[452]

Wearable headsets could potentially interpret EEG signals in a basic way to describe stress levels for users and then use the information to test and optimize the ergonomic design of spaces such as aircraft cockpits to minimize stress and optimize cognitive performance. At ISAE-SUPAERO (the National Higher French Institute of Aeronautics and Space), researchers are using simple neuroergonomics to speed up pilots' reactions to warning systems, cutting reaction times by one-third. Neuropriming for athletic performance and potentially mental conditioning is another application. This technology involves applying transcranial direct current stimulation (tDCS), or noninvasive and pain-free electric currents delivered from a headset, to a user's brain prior to starting a workout; the stimulation primes the brain to establish neuronal connections that optimize athletic performance.[453] While tDCS has been used in the clinical treatment of various neurological diseases such as Parkinson's, Halo Neuroscience is one of a number of startups interested in taking the scientific principles of the clinical treatment and applying it to consumer devices. Its Halo headset primes the user's brain for 20 minutes before starting a workout.

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446 Paul S. Larson, "Deep brain stimulation for movement disorders," *Neuroprosthetics*, 2014, Volume 11.

447 Alexander Green, *Deep brain stimulation: A way to rebalance neural circuits*, International Neuromodulation Society; and "Deep brain stimulation," *Science Daily*.

448 Majed Aldehri et al., "Deep brain stimulation for Alzheimer's disease: An update," *Surgical Neurology International*, March 2018; Catherine Offord, "Deep brain stimulation improves depression symptoms: Study," *The Scientist*, October 7, 2019; and *Deep brain stimulation for anxiety disorders in adults*, NYU Langone Health.

449 This is at an early stage, and we did not size the potential.

450 Jennifer Kite-Powell, "Using brain signals to read emotions," *Forbes*, June 25, 2013; and *Carnegie Mellon researchers identify emotions based on brain activity*, Carnegie Mellon University, June 19, 2013.

451 Patrick O'Rourke, "Can Toronto-based InterAxon's brain-sensing headband Muse help people relax?," *Financial Post*, April 14, 2015.

452 Olave Krigolson, "How scientists will track astronauts' mental performance on Mars missions," *Space Daily,* February 26, 2020.

453 *How to use Halo Sport 2*, Halo Neuroscience.

Hypothetically, if neuroprosthetics are able to feed light signals to the optic nerve, it would also be possible to transmit other signals, like infrared, to augment vision even in individuals with 20/20 vision. French company Pixium Vision and Stanford University have produced infrared bionic vision implants. A microprocessor embedded in the eye takes infrared light and then translates it as electrical stimulation to underlying optic nerve cells; infrared light is used because signals from ambient light are not strong enough to be detected.[454]

Consumer devices

A number of consumer applications of biomachine interfaces could be promising. In gaming, the Emotiv headset collects users' brain signals and then assesses and calibrates them to control a simple action such as lifting an object.[455] Hypothetically, brain-wave-reading technologies could control phones and computers. Most likely to be commercialized for consumer use is using brain control for augmented reality (AR) wearables such as smart glasses.[456] Demand for brain-controlled devices may be limited because there are, for now, easier forms of control such as eye tracking and even conventional touch-based smartphones; this may mean that investment is not forthcoming to power advances in this area. Wearable headsets could be used in marketing to collect consumers' reactions to different products and retail channels. Current technologies would support very basic interpretations, such as levels of stress or excitement. In the future, theoretically headsets could be used to interpret brain signals of pets in a bid to understand their mental and emotional state.

Biomachine interfaces may develop in defense

Potential biomachine applications in defense could hypothetically include using brain-to-brain communications on the battlefield or integrated exoskeletons with extra appendages that are controllable via neural connection. In March 2018, Darpa announced a four-year Next-Generation Nonsurgical Neurotechnology program, known as N3, with $20 million allocated to six teams at different universities and research centers to develop cutting-edge biomachine interfaces.[457] The project goals are truly straight from science fiction. One project group is looking at ways to genetically engineer brain cells to develop iron-activated proteins that emit infrared light, which can then be manipulated by magnetic headsets to stimulate specific cells with the hope of conveying images into the brain. While such projects are highly speculative, they illustrate growing interest in the military and defense industry in how to use emerging technology.

[454] Eliza Strickland, *A new bionic eye: Infrared light-powered retina implant coming*, IEEE Spectrum, April 2015.
[455] Jane McGrath, *How the Emotiv EPOC works*, How Stuff Works.
[456] Leopoldo Angrisani et al., *Wearable augmented reality and brain computer interface to improve human-robot transactions in smart industry: A feasibility study for SSVEP signals*, 4th International Forum on Research and Technology for Society and Industry (RTSI), Palermo, Italy, September 10–13, 2018; and Megan Scudellari, *Facebook closer to augmented reality glasses with brain implant that decodes dialogue from neural activity,* IEEE Spectrum, July 30, 2019.
[457] *Six paths to the nonsurgical future of brain-machine interfaces*, Darpa, Mary 20, 2019; and Shelly Fan, *DARPA's new project is investing millions in brain-machine interface tech*, Singularity Hub, June 5, 2019.

Unaligned DNA sequences letters on LCD screen
© Alanphillips/E+/Getty Images

6.7. Biocomputing

Molecular biology and modern computer science are interacting in a dynamic way to create entire new functionalities, including the birth of biocomputing. We define biocomputing as technologies that use biological molecules to perform data and analytics functions traditionally achieved in silicon-based devices. For Silicon Valley and other global tech centers, some regard this as the new technological frontier; biocomputing was the final topic of the keynote speech at Microsoft's Ignite conference in 2019.[458]

The two main applications of biocomputing explored in this chapter are nucleic acid data storage and biology-based parallel processing.[459] Commercially usable nucleic acid storage could technically be available after 2025, but it would be rudimentary and not likely to have significant commercial impact in this time frame. By 2050 to 2075, the technology could have potential direct annual impact of between roughly $5 billion and $15 billion. Biology-based parallel computing is not likely to become commercially viable for several decades. There has been progress in proof-of-concept demonstrations, but substantial challenges must be faced before these technologies can compete with silicon devices and be commercialized. It may well be that, even in the long term, biocomputing will complement rather than replace silicon.[460]

There is potential in biological storage and computing

We look at two types of applications in biocomputing: nucleic acid data storage and biology-based parallel computing.

Nucleic acid data storage

Nucleic acid data storage is data storage in strands of DNA. (Using RNA for storage is possible, but DNA is more stable.) Today, data are stored on semiconductor and magnetic devices, but imagine a future in which automated machines store information by synthesizing strands of DNA; the base pairs could encode text, pictures, and even movies. A section of DNA where the data are stored would need to be identified, the pairs read, and the data returned to your computer. Because it is—for now—harder to manipulate base pairs in order to store data biologically than to use conventional silicon-based information storage, it is highly likely that nucleic acid data storage will not replace conventional data storage altogether, but instead be used in cases involving large quantities of data that do not need to be accessed quickly.

This may sound far-fetched, but the application is on its way. The first encoding of a 659-kilobyte book on DNA was carried out in 2011 at Harvard University, and the next year the team demonstrated far higher accuracy and much more data stored—more than five megabytes.[461] In 2013, the European Bioinformatics Institute reported accuracy of

[458] Michael Miller, "Microsoft Research: Machine teaching optical computing, machine-human interaction, and more," *PC Magazine*, November 13, 2019.

[459] Simson Garfinkel, "Biological computing," *MIT Technology Review*, May 1, 2000.

[460] Two other emerging technologies are worth mentioning that are not in the scope of our analysis. The first is neuromorphic computing, which is the application of brain-based principles of gradient signals to traditional circuits. See Scott Fulton III, *What neuromorphic engineering is, and why it's triggered an analog revolution,* ZDNet, February 2019. Unlike the applications we investigate that use biological substrates, neuromorphic computing uses biological principles from studying the brain to create more advanced version of silicon-based electronics. The second emerging technology is bio-nanorobotics and biologic reactors, or the use of biochemical properties of molecules or cells to detect environmental signals and transduce certain actions. Unlike the applications we investigate, the most direct use of this application would be acting as an element of bio-nanorobotic engineering. In the distant future, bio-nanorobotic computers may emerge. See Simson Garfinkel, "Biological computing," *MIT Technology Review*, May 1, 2000.

[461] Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016.

100 percent.[462] Now private-sector companies, including Intel, Micron, and Microsoft, are investing in this technology.

Advances in this area could be one way to solve the rising challenge of how to store all the data now being generated. Every minute, 16 million texts are sent and more than half a million photos shared via Snapchat. Every day, 2.5 quintillion bytes of data are produced globally.[463] Some estimates suggest that the world could run out of silicon for data storage by 2040.[464] DNA storage presents a potential solution because DNA is extremely compact. DNA is about a million times denser than conventional hard-disk storage; technically, engineering constraints aside, one kilogram of DNA could store all of the world's data today.[465] Another property of nucleic acid data storage is the longevity of the medium given the right storage conditions.[466] Nucleic acid data storage could ensure that any data not regularly accessed could be stored safely and securely in the very long term—on the scale of dozens or even hundreds of years.[467]

Realistically, however, significant challenges must be overcome before nucleic acid storage can be used commercially. First, the cost of storage currently is prohibitively high, both in synthesizing (writing) and sequencing (reading) the data. Encoding a single megabyte of data via DNA cost $3,500 in 2017, compared with 2 cents on a hard disk.[468] Costs could come down rapidly, as they have with silicon storage—a megabyte of DNA cost $12,400 to code in 2012.

A second challenge is the current lack of a distributable automated system to write and read, and then access, nucleic acid data. Organizations or corporations hosting these data would need equipment capable of converting them directly from electronically stored data into DNA molecules. This requires complex fluid dynamics engineering for accurate DNA synthesis. This challenge is not, however, insurmountable. Recent research indicates that there has already been significant progress. A collaboration between the University of Washington and Microsoft demonstrated an end-to-end automated version of the process in 2019 that links the writing and reading functions directly to a computer—no handling of DNA in pipettes was necessary.[469] A final challenge is that DNA data storage is still not as fast as electronic data storage despite continuing advances in DNA synthesis and sequencing, and this prevents timely recording and extraction of data. Current DNA synthesis techniques take about 400 seconds to add each base pair, compared with almost instantaneous coding of 0 or 1 in conventional silicon-based computing. A typical hard disk drive has read/write speeds of up to 200 megabits per second.[470]

Biology-based parallel computing

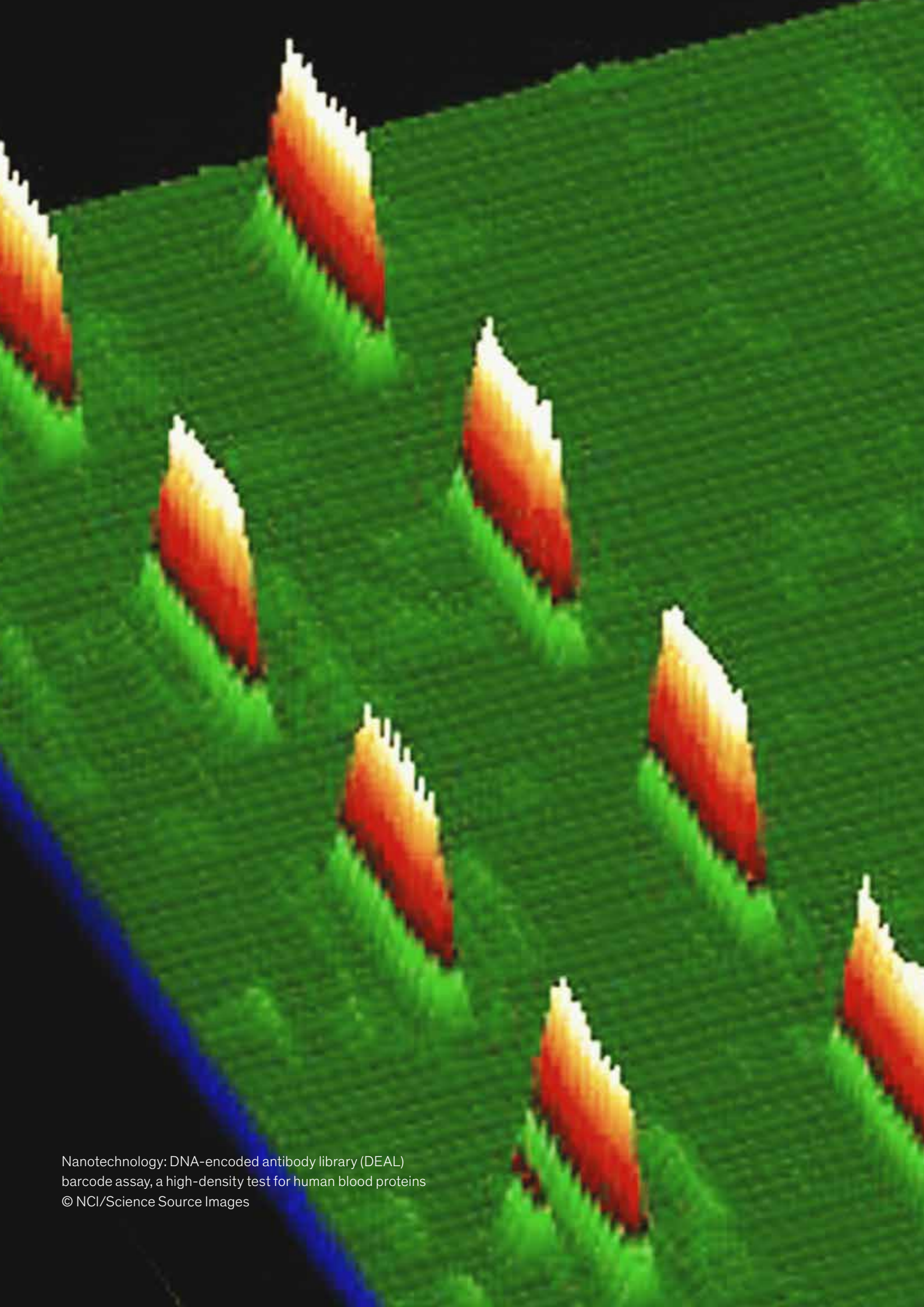
In the future, a biologic parallel computer may use biomolecules to test many solutions in parallel simultaneously, and therefore come up with an answer much more quickly than traditional computing. Biology-based parallel computing broadly uses designed molecules or cells as analogs for solutions or logic operations, thereby creating new algorithmic approaches for solving problems that rely on biologic substrates.

462 Nick Goldman et al., "Towards practical, high-capacity, low-maintenance storage of digital information in synthesized DNA," *Nature*, February 2013, Volume 494, Issue 7435.
463 Bernard Marr, "How much data do we create every day? The mind-blowing stats everyone should read," *Forbes*, May 21, 2018.
464 Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016.
465 Ibid.
466 *DNA data storage*, Hightech.
467 Monya Baker, "DNA storage breaks records," *Nature*, August 6, 2012; and "Test-tube data," *Economist*, January 26, 2013.
468 Ed Yong, "This speck of DNA contains a movie, a computer virus, and an Amazon gift card," *The Atlantic*, March 2, 2017; and Lucas Mearian, "CW@50: Data storage goes from $1M to 2 cents per gigabyte," *Computer World*, March 23, 2017.
469 Jennifer Langston, *With a "hello," Microsoft and UW demonstrate first fully automated DNA data storage*, Microsoft, March 21, 2019.
470 Andy Extance, "How DNA could store all the world's data," *Nature*, September 2, 2016; and Lisa Johnson, *An explanation of read and write speeds*, Lifewire, January 26, 2020.

The advantages of this application are greater energy efficiency and speed. Researchers at McGill University created a chip with microscopic channels coated with myosin, a molecular motor found in muscle cells, through which protein filaments were able to travel.[471] By configuring the device's layout, researchers were able to set up the "traveling salesman problem" in which the algorithmically complex question is asked, "What is the best route to take to visit all locations at least once, while returning to the starting location?" Whereas a traditional computing approach would require testing every single possible solution out of the numerous possible routes, with the protein-based parallel computation method, the proteins' final exit channels showed answers to optimized travel routes more quickly than conventional computing would.[472] Furthermore, the biocomputing chip identified the answer while using 10,000 times less energy than a traditional computer in solving the same problem. While the proof-of-concept experiments tackled simple problems that had less space to demonstrate calculation speed, researchers strongly believe that future complex problems that would be difficult or even impossible to solve with traditional computing could be more quickly calculated by parallel processing biocomputing.

Interest in this nascent area is growing. As part of EU Horizon 2020, its flagship innovation plan, the EU launched a five-year project called Bio4Comp in 2017 with an initial investment of €6.1 million that aims to create a biocomputer prototype. DNA storage is attracting interest from governments and defense departments. For instance, Darpa has made $15.3 million of grants to players investigating DNA storage.[473]

[471] Sheena Goodyear, "Biological supercomputer model could change how we solve complex problems," CBC News, February 26, 2016.
[472] Tim Sandle, "Biotech used to create parallel computers," *Digital Journal*, July 18, 2017.
[473] Megan Molteni, "The rise of DNA data storage," *Wired*, June 26, 2018.



Nanotechnology: DNA-encoded antibody library (DEAL) barcode assay, a high-density test for human blood proteins
© NCI/Science Source Images

Technical appendix

This appendix provides additional details on the key assumptions, calculations, methods, and data sources used to estimate the potential direct economic impact of biological applications. It comprises the following sections:

— Scope and factors in our estimations of potential economic impact

— Methodology for micro-to-macro analysis based on use cases

— Methodology for extrapolation of potential economic impact in different time horizons

— Methodology for estimating the timing of the adoption acceleration point

Scope and factors in our estimations of potential economic impact

Our analysis is not a forecast or prediction of future value created, but rather a set of estimates of the potential for economic impact of bio innovation given certain assumptions. All assessments are annual and global, and include only direct impact based on a library of about 400 use cases. Our estimates assume that there are no global regulatory bans on the technologies included in our scope and that R&D continues. These estimates are particularly sensitive to assumptions about adoption rates and to the value of different types of gains, including, for instance, improved outcomes in health, and cost savings in a number of domains.

We sized only direct impact biological applications that are scientifically conceivable today and could plausibly be adopted by 2050

We estimated direct impact from the library of around 400 use cases we identified. To compile the library, we first defined which technologies fell within the scope of the Bio Revolution as defined in this research. We then identified a pipeline of applications that could produce tangible benefits. The library includes use cases that are scientifically conceivable today and could plausibly be adopted by 2050. It excludes applications that are not scientifically conceivable today (for instance, steel production via biological means) or are unlikely to have material commercial impact by 2050. All technologies described in chapter 1 are included. We excluded technologies that are already commercially mature. We tested the use cases with a range of experts to better understand economic potential and adoption timing.

For applications that are fully based on technologies included in our use cases, such as gene therapy, we have estimated the entire potential direct economic impact. In cases where existing technologies are improved, such as optimizing fermentation processes, we sized the marginal benefit. So, for instance, we estimated the impact of enhanced production of protein biologics with new genomic-related technologies, but not the impact on health of all protein-based biologics at large.[474]

[474] We do not consider protein-based biologics in the scope of our research, although they are biological in nature.

This library is extensive, but not exhaustive. We acknowledge that other use cases may have an impact that we cannot identify today. For instance, there are applications that we cannot identify today due to limited public information—many innovations are being developed in private labs or in the defense industry where confidentiality is a major factor. In addition, while we sought input from a wide range of experts, that input was not exhaustive. Unforeseen breakthroughs in biological science and technology could unlock additional economic impact or accelerate scientific research and commercialization timelines. The visibility of the pipeline of future applications differs among domains. For instance, the human health pipeline is clearer because health is a heavily regulated public good. The path ahead for novel materials and chemicals, which are largely being developed by private-sector players that want to maintain confidentiality, is less visible.

In some instances, we describe potential uses but do not estimate the potential size of their impact, largely because an application is unlikely to be commercialized by 2050; one example is biology-based parallel computing. We nevertheless chose to discuss such use cases qualitatively to demonstrate the potential breadth of biological applications. In some rare instances, including biocomputing, the commercialization timeline was difficult to assess, and estimating the size of the potential economic impact required unavailable data, methodologies, or both. In these cases, too, we confined ourselves to a qualitative discussion.

Estimates of potential direct economic impact are relative to the 2020 economy and not forecasts

We estimated potential direct economic impact for the future relative to the 2020 economy, including metrics such as global population and disease burden. This approach enables us to make comparisons of the magnitude of that economic impact without introducing additional scenarios based on variables such as future population growth, demographic shifts, inflation, changes in market size, or changes in the disease burden. Data sources for the 2020 context include population estimates from the United Nations, disease burden estimates from the Institute for Health Metrics and Evaluation (IHME), and market-size estimates from market reports. We note that our estimates are likely to underestimate the value of markets that are growing and to overestimate cases where disease burden could be reduced or even eradicated by other means, for instance certain infectious diseases.

We recognize that economic impact may not necessarily translate into GDP

We assessed the annual potential economic impact from the perspective of the overall economy, including all participants in the value chain. Our estimates do not represent GDP or market size, but rather economic impact, including consumer surplus. We also note that we did not subtract R&D investment and development costs from value gains because we assumed they are already priced into the benefits.

Methodology for micro-to-macro analysis based on use cases

We grouped the library of around 400 use cases into 130-plus broader application categories in order to estimate their potential direct economic impact. Each assessment of applications was the product of three factors: volume, adoption rate, and value gained.

— **Volume.** As noted, volume is based on 2020 metrics for population, markets, and the global burden of disease, for instance.

— **Adoption rate.** For each application category, we ranged both adoption levels (low and high values that are ambitious but achievable) and timing of adoption to reflect a high level of uncertainty regarding adoption rate. Where possible, we used sector-specific analogs for potential adoption levels and timing, and we tested our assumptions with experts. We took geography into account in our assumptions on the timing of adoption, differentiating between high-income and low-income countries.

— **Estimating value gained.** For purposes of comparison, we estimated value for different types of gains in economic terms in the following main categories:

- Cost productivity. We defined cost productivity as the reduction in cost required to produce or purchase an existing product or service.

- Improvements in quality. In order to estimate the value of products and services that offer greater benefits, such as improved quality, than current alternatives, we estimated the additional value of these new products and services by customers' willingness to pay a price premium. We then scaled this to current spending levels in the product or service category.

- Health improvements. We translated impact on health into economic terms by looking at a reduction in the global disease burden that could be delivered by increasing efficacy of health treatments. Our calculation is not based on health spending or the sizes of pharmaceutical markets, but rather the potential economic impact experienced by all participants in the value chain. Our estimate does not account for cost of technologies. Efficacy refers to the percentage of intended disease reduction achieved when an intervention is adopted. We used current research on diagnostics and therapies to inform our assumptions on efficacy rates. We measured the disease burden using disability-adjusted life years (DALYs), primarily taken from 2017 data on the Global Burden of Disease compiled by IHME. The DALY measure includes years lived with disability (based on the number of individuals living with disease in that year) and years of life lost (the entirety of life for those dying in a year from a disease). In cases where DALY data were not available, we extrapolated from available metrics such as the percentage of births where monogenic disease was present. To translate reduced disease burden into economic metrics, we applied GDP-based values for high- and low-income countries.[475]

  This methodology enabled us to size applications very broadly, but we acknowledge that it has some limitations. We did not, as noted, project changes in the burden of disease, but rather assumed a steady state. We acknowledge that this may mean that we underestimate the economic impact of diseases that are imposing a growing burden and overestimate the economic impact of diseases that may be eradicated, including certain infectious diseases. We also note that by valuing the entirety of life lost in the year in which a death occurs, we include potential that is not realized until later. This also assumes that an individual saved from one illness does not develop another that causes premature death or disability.

- Environmental benefit. We defined this as the reduction of carbon emissions valued using the cost of carbon credits.[476] Some applications, including alternative (animal-free) proteins, reduce emissions, while others sequester existing carbon in the atmosphere. Given conservative adoption rates for both, we do not have concerns about double counting. One limitation of this methodology is using a single carbon credit value at a time when there is no universal, uniform carbon tax in place. Another is the fact that it does not account for other environmental benefits such as reduced use of water, land, and energy use, or the preservation of natural resources, which we did not factor into our sizing.

[475] Based on 2017 World Bank data on per capita GDP by country. We calculated weighted averages by population to match the IHME's Global Burden of Disease country categories of high and low socio-demographic index (SDI). The resulting assumptions are approximately $23,000 per DALY for high-SDI countries and $4,000 per DALY for low-SDI countries. We made one exception; for use cases related to gene drives in lower-income countries, we assumed $1,000 per DALY.

[476] For consistency, we used the 2019 California price per metric ton of CO_2, $15.

Methodology for extrapolation of potential economic impact in different time horizons

In each application category, we estimated low and high levels of peak adoption—the level at which adoption plateaus when a product or service is mature. We also estimated the time it may take to reach peak adoption. This is a simplification that allows us to arrive at a feasible estimate of the potential economic impact; we recognize that adoption peak levels could change with shifting product features, customer demographics, and so on.

Using expert input and historical analogs, we extrapolated our assessed impact to different time horizons by estimating how long it might take for an application to achieve scientific feasibility, commercial availability, and then peak impact.[477] We acknowledge that adoption levels and timing may be subject to many uncertainties, including shifting product features and customer demographics, that may not be fully captured in our assessment. Adoption was modeled based on innovation-adoption curves that varied depending on the type of use case to allocate the impact to different time horizons.

We based our assessment of the time to peak impact for each application category on three components: time to scientific feasibility, time from scientific feasibility to commercial availability, and time from commercial availability to peak adoption (Exhibit A1).

— **Scientific feasibility.** We defined this as experimental success in the target population (for instance, in the case of human health, success in humans rather than in mice models). For applications where we could not identify proof of concept in academia or industry, we assessed feasibility using sector-specific analogs and expert interviews that estimate how far away scientific feasibility might be.

— **Commercial availability.** We defined this as the market launch of a product or service by at least one startup or incumbent (we recognize that true commercial availability includes profitability and a favorable regulatory environment). For applications where we could not identify commercial availability in this way, we estimated the potential time required from scientific feasibility to commercialization based on historical analogs and expert interviews.

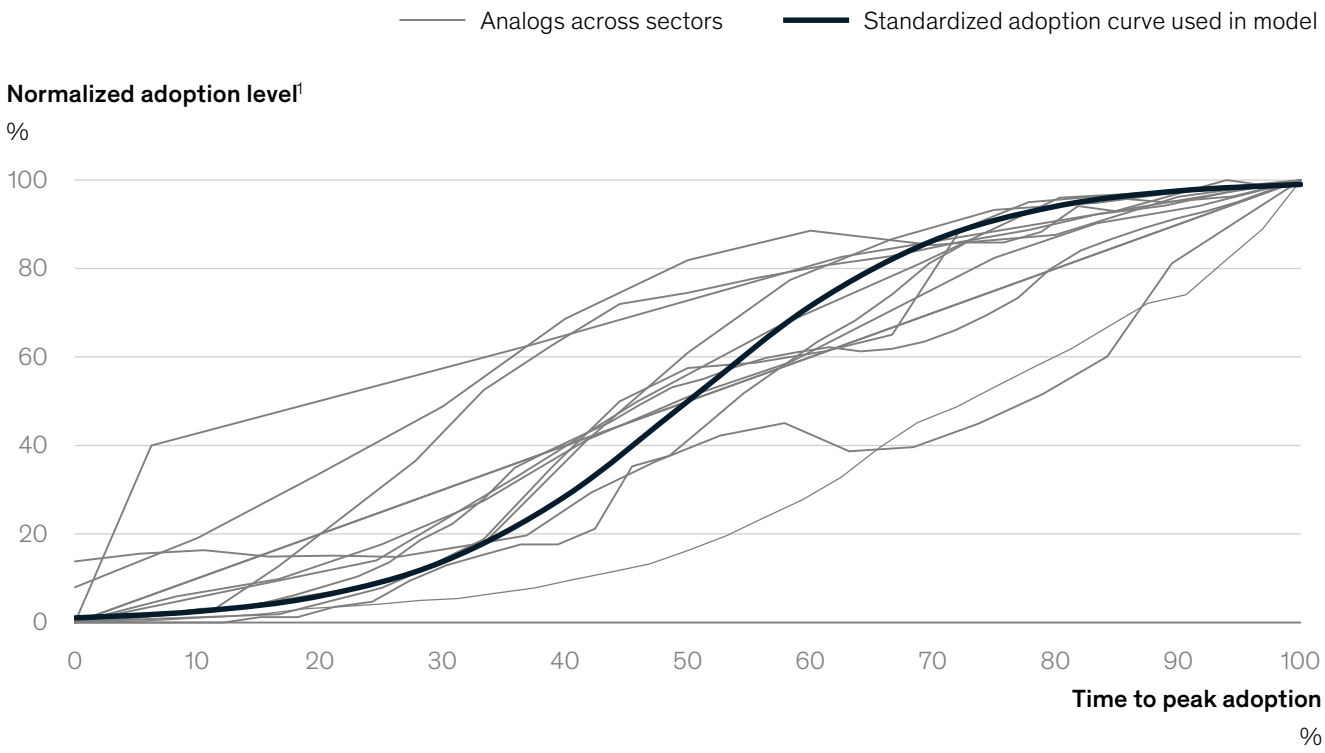
— **Peak adoption.** We defined peak adoption as the point at which product or service adoption plateaus. Given that none of the applications we assessed have reached peak adoption, we used sector-specific historical analogs for other innovations to assess the potential time from commercial availability to peak adoption.

Based on the timelines assessed, we then allocated potential economic impact for each micro-assessment to different periods of interest based on a standardized adoption curve matching historical analogs. The periods for impact discussed throughout the report are the short term (2020 to 2030), medium term (2030 to 2040), and long term (2040 to 2050).

[477] We recognize that not all bio innovations will be launched into a traditional "commercial" market, for instance those that are deployed by the public sector. We use "commercial availability" and "market launch" to refer to the general idea that the bio innovation has passed sufficient testing that it can now be made available to the target population, in which case the diffusion factors apply, for instance, whether the innovation is superior to alternatives.

Exhibit A1

We applied a standardized adoption curve based on the analogs (timing agnostic).



1. Normalized to peak adoption.

Source: McKinsey Global Institute analysis

Methodology for estimating the timing of the adoption acceleration point

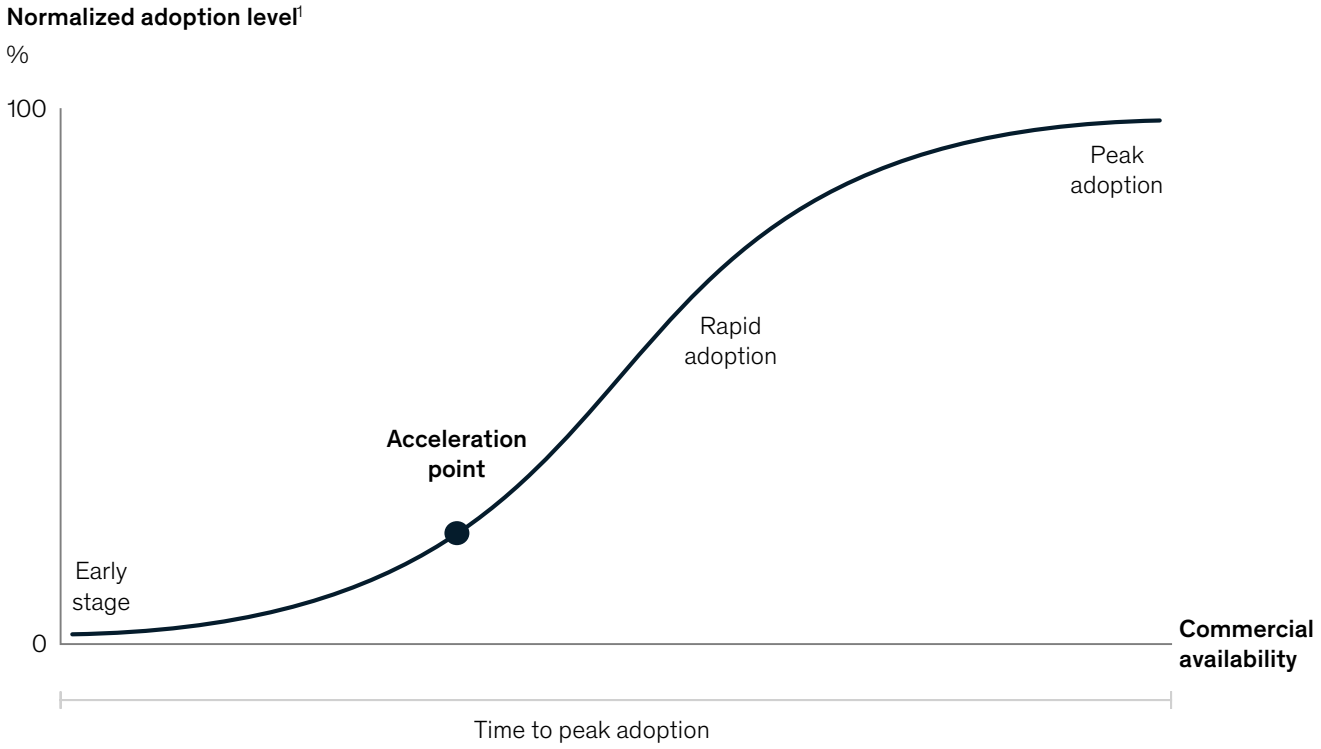
Once the adoption curves for individual micro-assessments are generated, we determined the timing of the growth point of adoption—the point at which adoption grows most rapidly—using the widely used Everett Rogers theory on diffusion and adoption of technological innovations (Exhibit A2).[478] We referred to this point as the "acceleration point," since it is where the second derivative of the sigmoid function for adoption reaches its maximum. Empirically, we observe that the successful adoption of an innovation generally follows an S-shaped sigmoid function curve. According to the theory, after 10 to 25 percent of a system's members adopt an innovation, adoption by the remainder is relatively rapid. In order to understand and compare relative adoption across time periods for various applications, we identified the acceleration point for each application based on its modeled adoption curve. We used the timing of this acceleration point to determine over what timeframe adoption might be expected to increase at a rapid rate.

[478] Everett M. Rogers, *Diffusion of Innovations*, 5th edition, New York, NY: Free Press, 2003; and Ismail Sahin, "Detailed review of Rogers diffusion of innovation theory and educational technology-related studies based on Rogers' theory," *Turkish Online Journal of Educational Technology*, April 2006, Volume 5, Issue 2.

Exhibit A2

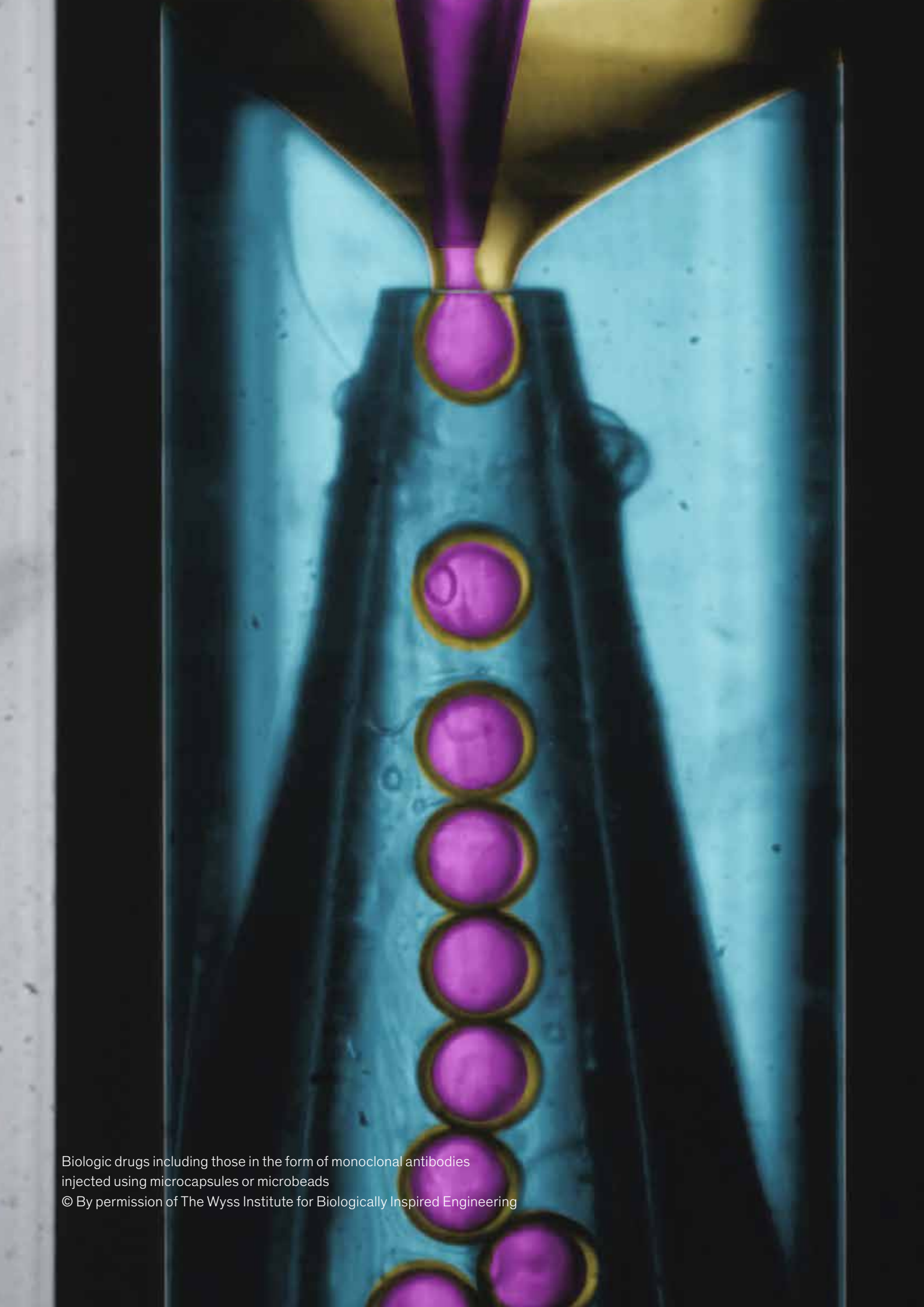
The acceleration point is when adoption starts to experience rapid growth.

Illustrative



1. Normalized to peak adoption.

Source: Everett M. Rogers, *Diffusion of innovations* (1st ed.), New York: Free Press of Glencoe, 1962; McKinsey Global Institute analysis



Biologic drugs including those in the form of monoclonal antibodies injected using microcapsules or microbeads
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Glossary

The definitions in this glossary come from a range of online sources, including research publications, scientific articles, and encyclopedias.

Allele. Any of the alternative forms of a gene that may occur at a given locus.

Bioinformatics. A hybrid science between computer science, biology, and statistics that involves the analysis of large amounts of biological data.

Biocomputing. This field of biology is defined as using cells and cellular components for computational processes (storing, retrieving, processing data).

Biomachine interfaces. This field of biology is defined as the connection of nervous systems of living organisms to machines, including in brain-machine interfaces.

Biomarkers. A measurable indicator such as a molecule, gene, or characteristic, by which a particular biological process can be identified.

Biomolecules. In our definition of biomolecules for this report, this covers the mapping and measuring of intra-cellular components (for example, DNA, RNA, and proteins) in the study of omics. We also include the engineering of intra-cellular components (for instance, genome editing).

Biosystems. This covers engineering at the cell, tissue, or organ level, including stem-cell technologies and transplantation use cases.

Carrier screening. Carrier screening is a genetic test used to determine if a healthy person is a carrier of a recessive genetic disease. It provides life-lasting information about an individual's reproductive risk and their chances of having a child with a genetic disease.

CAR T-cell (chimeric antigen receptor T-cell). CAR T-cells are genetically engineered T-cells which express artificial chimeric antigen receptors on their surface. These engineered T-cells enable a patient's own immune system to identify and destroy targeted cells.

Cell-free DNA/RNA analysis. Often abbreviated to cfDNA/cfRNA, this is the sequencing of DNA or RNA outside a cell, in the bloodstream, for instance.

Checkpoint inhibitor. A type of drug that helps to activate a patient's immune system. This works by blocking immune checkpoint proteins that are involved in deactivating a patient's immune response.

CRISPR-Cas9. Clustered regularly interspaced short palindromic repeats and CRISPR-associated protein 9. This tool uses a small piece of RNA with a short "guide" sequence that attaches to a target sequence of DNA and to the Cas9 enzyme. The Cas9 enzyme cuts the targeted DNA at the targeted location, which enables genetic material to be added or deleted.

CRISPR-Chip. A system that immobilizes CRISPR complexes on the surface of graphene-based transistors, which allows for the electronic identification of specific target genes.

Cultured meat. Meat produced by in vitro cultivation of animal cells.

DNA. Short for deoxyribonucleic acid, this is an organic chemical found in all cells and in many viruses. DNA acts as the main carrier for genetic information.

EEG. Short for electroencephalogram, this technique records brain wave patterns. It works by attaching small metal discs to the scalp to measure electrical activity.

ELISA. Short for enzyme-linked immunosorbent assay, this technique detects and measures the amount of a substance in a solution such as serum. It uses antibodies linked to enzymes that can produce a color change or other measurable effect.

Epigenomics. This is the study of the epigenome, specifically epigenetic modifications that affect gene expression such as DNA methylation and histone modification. This can direct such actions as turning genes on or off, and controlling the production of proteins in particular cells.

Fermentation. This is an anaerobic metabolic process in which energy can be released from carbohydrate (such as glucose) even if oxygen is not available. During this process, the carbohydrate is converted into alcohol or acid. Fermentation occurs in yeast cells, bacteria, and the muscle cells of animals.

Flow cytometry. A laser-based technology that counts, sorts, and profiles cells or particles within a liquid suspension.

Gene array. Scientific equipment that contains a collection of nucleic acids at specific locations, which allows for measurement of analysis of the nucleic acids.

Gene drive. Technology that uses genetic engineering to enable a specific genetic variant to be passed from parent to child at a higher-than-normal rate (up to 100 percent).

Genome sequencing. A process for determining the order of DNA nucleotides within a DNA sequence.

Genome-wide association studies. These studies find associations between a particular human trait and variation in genetic sequence throughout the genome across a large population. In these studies, people who have a particular disease and many who don't are sequenced in order to find areas of consistent differences. If such areas are discovered, this helps scientists to zero in on parts of the genome that are responsible for the risk of disease.

Genomics. This is the study of genes and their functions, and techniques related to them. The genome consists of the full genetic complement of an organism—its DNA.

Genotype. An organism's collection of genetic material.

Germline editing. This is gene editing of an embryo, egg, or sperm such that changes are inherited by all future generations.

Glycomics. This relates to the glycome, which is the structure and function of the complete set of glycosylated products.

GMO (genetically modified organism). A GMO is an organism whose genetic material has been altered or modified. In GM crops, DNA from foreign organisms such as bacteria is introduced.

Guide RNAs or gRNAs. RNA sequences that guide Cas nuclease to a target region of DNA.

High-performance liquid chromatography. This is a form of column chromatography that separates, identifies, and quantifies components dissolved in a liquid solvent with a high analytical resolution.

In utero gene editing. This is editing of genes in a fetus while in the uterus, which has the advantage of being able to use the normal developmental properties of the fetus to accomplish efficient gene editing.

In vitro fertilization (IVF). A type of assisted reproduction technology in which an egg is fertilized by sperm outside the body.

Induced pluripotent stem cells (iPSCs). These are adult cells (for instance, skin cells) that are reprogrammed into an embryonic stem cell-like state that enables the development of unlimited amounts of any type of human cells.

Lipidomics. This is the comprehensive identification and quantification of the complete set of lipids (the lipidome) of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time.

Magnetic resonance imaging (MRI). MRI is a medical imaging technique using magnetic fields and radio waves to create detailed images of the inside of the body.

Magnetoencephalography (MEG). This is a noninvasive neuroimaging technique for direct mapping brain activity by recording magnetic fields generated by electrical currents occurring naturally in the neurons of the brain.

Marker-assisted breeding. Marker-assisted breeding uses DNA markers associated with desirable traits to enable breeders to select a trait of interest without using transgenic approaches. Therefore, marker-assisted breeding doesn't produce GM organisms.

Mass spectrometry. This is a tool used for measuring the mass-to-charge ratio of one or more molecules present in a sample. Mass spectrometers can be used to identify unknown compounds by determining their molecular weight, to quantify known compounds, and to determine the structure and chemical properties of molecules. It is used in epigenomics, proteomics, metabolomics, glycomics, and microbiomics.

Mesenchymal stem cells. These are stem cells that are found in various tissues (such as bone marrow) that can differentiate into a variety of cell types, such as bone, cartilage, muscle, and fat.

Metabolomics. This is the comprehensive identification and quantification of the complete set of metabolites (substrates, intermediates, and products of metabolism) of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time.

Microarray. This is a high-throughput screening method where the DNA sequences representing the large number of genes of an organism that are arranged in a grid pattern for detection in genetic testing.

Microbiomics. This is the comprehensive identification and quantification of the complete set of microbes (the microbiome) of a biological system (such as the human gut or skin, and in the soil around farms) at a specific point in time.

Monoclonal antibodies. These are man-made antibodies of predetermined specificity against targets made by identical immune cells derived from a unique parent cell.

Monogenic. A monogenic disease is caused by mutations in a single gene.

Neuroergonomics. This is a research field that investigates the human brain functions—perceptual, cognitive, and motor functions—in relation to behavioral performance in natural environments and everyday settings.

Neuroprosthetics. Hybrid bionic systems that link the human nervous system to computers, thereby providing motor control and restoring lost sensory function of artificial limbs.

Next-generation sequencing (NGS). This is a catch-all term that refers to a range of modern high-throughput DNA sequencing technologies in which millions or billions of small DNA fragments can be sequenced in parallel. The sequences of these small fragments will be pieced together by mapping against the human reference genome.

Noninvasive prenatal test (NIPT). Also known as noninvasive prenatal screening or NIPS, this is a noninvasive method for determining the risk that a fetus will be born with certain genetic disorders, primarily used for chromosomal disorders such as Down syndrome, by analyzing small cell-free fetal DNA fragments circulating in a pregnant woman's blood.

Nuclear magnetic resonance (NMR) spectroscopy. An analytical technique for determining molecular structures. Applications include determining the content and purity of a sample as well as its molecular structure, and metabolomics.

Nucleotides. These are the chemical compounds that are the basic structural units of RNA and DNA.

Omics. This is a collective term for technologies that allow the comprehensive identification and quantification of the complete set of molecules (eg, proteins, carbohydrates, lipids) of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time.

Omics and molecular technologies. We define this term to cover the study of omics as well as technologies to engineer (design, synthesize, or modify) the same "omes."

Outcrossing. This is the transfer of genes from genetically engineered plants into conventional crops or related species in the wild.

Phage. Also known as bacteriophage, this is a virus that infects and replicates within bacteria.

Pharmacogenomics. This is the use of an individual's genomic profile to optimize the choice of drugs and doses by physicians.

Phenotype. This is an organism's observable characteristics that could be influenced both by the genes of the organism and the environment.

Polygenic. Polygenic diseases are caused by more than one gene. Examples of polygenic conditions include hypertension, diabetes, and coronary heart disease. There are often many environmental factors, too, making it more difficult to discern to what degree a disease is genetic even when the multiple genes are identified.

Preimplantation genetic testing. This is genetic testing of an embryo prior to embryo transfer (to a uterus) during IVF. This can be done to test for single gene disorders such as cystic fibrosis (preimplantation genetic diagnosis, or PGD) or overall chromosomal abnormalities such as Down syndrome caused by an extra chromosome (preimplantation genetic screening, or PGS).

Proteomics. This is the comprehensive identification and quantification of the complete set of proteins of a biological system (cell, tissue, organ, biological fluid, or organism) at a specific point in time.

Regenerative medicine. The process of replacing, engineering, or regenerating human or animal cells, tissues, or organs to restore or establish natural function.

Reverse transcription polymerase chain reaction (RT-PCR). A laboratory technique used to make large-scale copies of specific segments of DNA molecules rapidly and precisely outside the body from a mixture of DNA molecules.

Ribonucleic acid (RNA). A biopolymer consists of ribose nucleotides (nitrogenous bases appended to a ribose sugar molecule) connected and forming strands of varying lengths. Unlike most DNA molecules composed of two biopolymer strands, RNA typically is a single-stranded biopolymer. RNA molecules play essential biological roles from translating genetic information encoded in DNA molecules into the cellular structures and molecular machines (ie, proteins) to regulating the activities of genes.

RNA interference (RNAi). This is an evolutionarily conserved gene silencing technique in which specific genes can be regulated and suppressed at the RNA level.

Single-cell omics. Any of the omics study can be done at a single-cell level. Analyzing a single cell makes it possible to discover mechanisms not seen when studying cells in bulk where variable signals from a heterogenous collection of cells in a typical sample would be averaged out.

Small interfering RNA (siRNA). Central to RNA interference, siRNA is a family of double-stranded non-coding RNA molecules, with typical lengths of 20 to 25 base pairs that regulate the expression of specific genes with complementary nucleotide sequences by degrading their mRNA transcripts, preventing translation.

Stem cell. A type of cell in a multicellular organism that has two capabilities: capable of self-renewal by producing indefinitely more cells of the same type, and capable of giving rise to many other kinds of cells in the body by differentiation.

Transcription activator-like effector nucleases (TALEN). TALEN are enzymes engineered to enable targeted modification of any DNA sequence in a large range of organisms.

Transcriptomics. This is the comprehensive identification and quantification of the complete set of RNA transcripts of a biological system (such as the human gut or skin, and in the soil around farms) at a specific point in time.

Whole genome sequencing. This is a method for analyzing the entire DNA sequence of an organism's genome.

Zinc finger nuclease. A class of engineered proteins that bind DNA and create double strand breaks at user-specified locations to facilitate targeted editing of the genome.

Nurse in surgery room putting drugs through an IV
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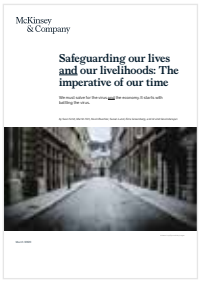

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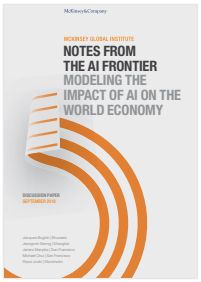
In response to the COVID-19 pandemic, this article argued that we must solve for the virus and the economy, but the task begins with tackling the virus.



Notes from the AI frontier: Modeling the impact of AI on the world economy (September 2018)

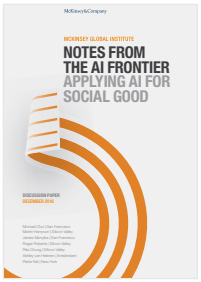
Artificial intelligence has large potential to contribute to global economic activity. But widening gaps among countries, companies, and workers will need to be managed to maximize the benefits.

Climate risk and response: Physical hazards and socioeconomic impacts (January 2020)

How could Earth's changing climate impact socioeconomic systems across the world in the next three decades? A yearlong, cross-disciplinary research effort at McKinsey & Company provides some answers.

A future that works: Automation, employment, and productivity (January 2017)

Automation is happening, and it will bring substantial benefits to businesses and economies worldwide, but it won't arrive overnight. Realizing automation's full potential requires people and technology to work hand in hand.



Notes from the AI frontier: Applying AI for social good (December 2018)

Artificial intelligence has the potential to help tackle some of the world's most challenging social problems. A library of about 160 AI social-impact use cases suggests existing capabilities could contribute to tackling cases across all 17 of the UN's sustainable-development goals.

Disruptive technologies: Advances that will transform life, business, and the global economy (May 2013)

Twelve emerging technologies—including the mobile Internet, autonomous vehicles, and advanced genomics—have the potential to truly reshape the world in which we live and work. Leaders in both government and business must not only know what's on the horizon but also start preparing for its impact.

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